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# Planetary Geology in the 1980s

National Aeronautics and  
Space Administration

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Joseph Veverka  
Cornell University

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**Planetary Geology Working Group (PGWG)  
(1981-1982)**

Joseph Boyce  
NASA Headquarters,  
Code EL  
Washington, DC 20546

Michael Carr  
USGS  
345 Middlefield Road  
Menlo Park, CA 94025

Mark Cintala  
Dept. of Geological Sciences  
Brown University  
Providence, RI 02912

Merton E. Davies  
RAND Corporation  
1700 Main Street  
Santa Monica, CA 90406

Everett Gibson  
Code TN7  
Johnson Space Center  
Houston, TX 77058

Ronald Greeley  
Arizona State University  
Dept. of Geology  
Tempe, AZ 85821

Kenneth Hamblin  
Brigham Young University  
Geology Department  
Provo, Utah 84602

Dag Nummedal  
Dept. of Geology  
Louisiana State University  
Baton Rouge, LA 70803

Stephen Saunders  
Jet Propulsion Laboratory, MS  
183/50  
4800 Oak Grove Drive  
Pasadena, CA 91103

Eugene Shoemaker  
USGS  
2255 North Gemini Drive  
Flagstaff, AZ 86001

Robert Strom  
University of Arizona  
Lunar and Planetary Laboratory  
Tucson, AZ 85721

Joseph Veverka, Chairman  
312 Space Sciences  
Cornell University  
Ithaca, NY 14853

Donald Wise  
Dept. of Geology  
University of Massachusetts  
Amherst, MA 01002

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J. Veverka



## Preface

This is the third document in a chronological series. The first appeared in 1970 at the request of NASA's former Planetology Program under the title, "A Strategy for Geologic Exploration of the Planets," edited by M. H. Carr and published as United States Geological Survey Circular No. 640. Then, as now, the objectives were to define the major goals of planetary geology and to set forth methods of meeting these goals. In 1976, the Carr study was updated with the publication of *A Geological Basis for the Exploration of the Planets*, edited by R. Greeley and M. H. Carr (NASA SP-417).

The purpose of the present report is to once more provide an update and a future projection, this time into the 1980s. The basic objectives of the original strategy laid out in 1970 and in 1976 have changed little. Rather, it is our approach to realizing these goals that has matured and expanded. Now that Voyager has ventured beyond the asteroid belt into the realm of the outer planets, we have become keenly aware that the detailed study of satellites can teach us much about the geologic evolution of solid bodies in general. When the 1976 report was written, the bizarre nature of Titan's surface was hardly suspected; we were not aware of the intense volcanic activity of Io, or of the possibility that Neptune's Triton may have an ocean of liquid nitrogen. Another new emphasis that will be found in this report concerns the developing perception that the investigation of small bodies—asteroids, comets, and small satellites—can reveal much about the processes that were important during the earliest stages of the solar system's history. The enhanced emphasis on satellites and small bodies does not imply that our traditional interest in the geology of Earthlike planets has decreased; rather, it is a sign that as our discipline grows we are able

to assimilate more and more diverse information in building a truer picture of the geologic evolution of the planets. We certainly expect that the 1980s will see a continuation of the vigorous effort to decipher the complex geologic history of Mars revealed by the Viking data. We also anticipate that as the quality of our geologic information concerning Venus continues to improve, a major goal of planetary geology research will be to understand the distinct evolutionary paths of Earth and Venus—two planets which at first sight appear to be similar in many of their bulk physical properties.

As before, this report is not concerned with advocating any particular spacecraft mission, or series of missions, nor does it outline a sequence of solar system exploration programs. Rather, it is restricted to defining the kinds of experiments, observations, and measurements that need be made by Earth-based, Earth-orbit, and spacecraft exploration techniques to address major issues of concern to planetary geology. It also discusses important goals of data analysis and data synthesis in the area of planetary geology.

This document was written by the Planetary Geology Working Group during 1981–1982. The Group attempted to produce a consensus document based on drafts of individual chapters and sections written by specific members (the individual contributions are identified in the Acknowledgments). We also received numerous comments on several draft versions of the report from many of our colleagues; we hope that this helpful criticism has enabled us to maintain a balanced and a representative perspective throughout this document.

J. Veverka

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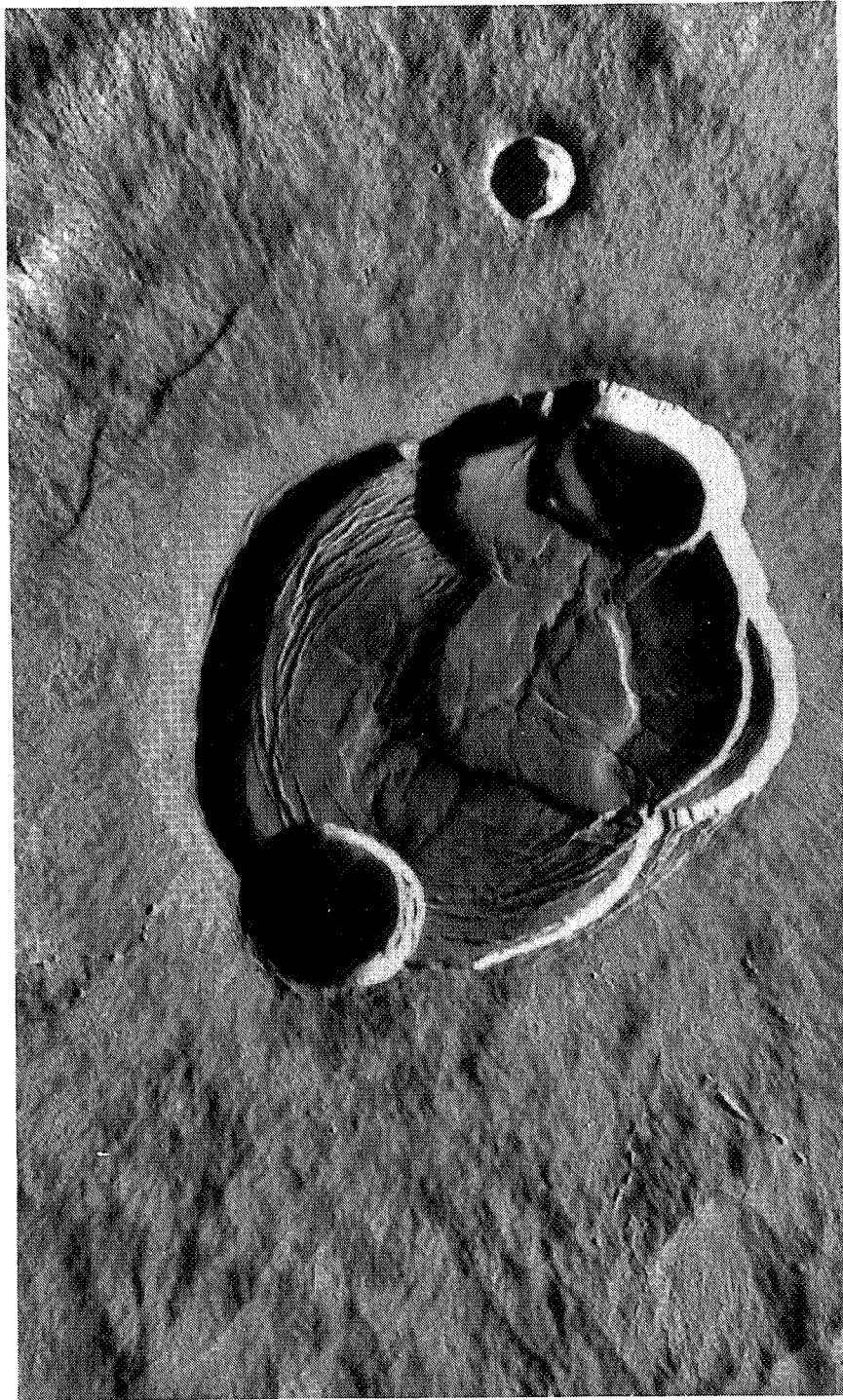
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# 1 Introduction

Planetary geology is the study of the origin, evolution, and distribution of solid matter condensed in the form of planets, satellites, comets, and asteroids. The term geology is used here in its broadest sense to mean the study of the solid parts of the planets. Aspects of geophysics, geochemistry, geodesy, cartography, and other disciplines concerned with the solid planets are all included in the general term.

This report is concerned with the kinds of experiments, observations, and studies that can be made through direct exploration of the entire solar system, although the discussion focuses on the terrestrial planets and the satellites of the outer planets. Planetary atmospheres are discussed only in relation to their evolution by the release of volatile gases through geologic processes and their influence on surface processes through time.

## 1.1. Relevance of Planetary Geology

The National Academy of Sciences (1966) identified three principal goals for the exploration of space: (1) to determine the origin and evolution of the solar system, (2) to determine the origin and evolution of life, and (3) to clarify the nature of the processes that shape our terrestrial environment. These objectives form part of the basic charter of space exploration of the National Aeronautics and Space Administration (NASA); planetary geology is an important component of each of these goals.

### 1.1.1. *Origin and Evolution of the Solar System*

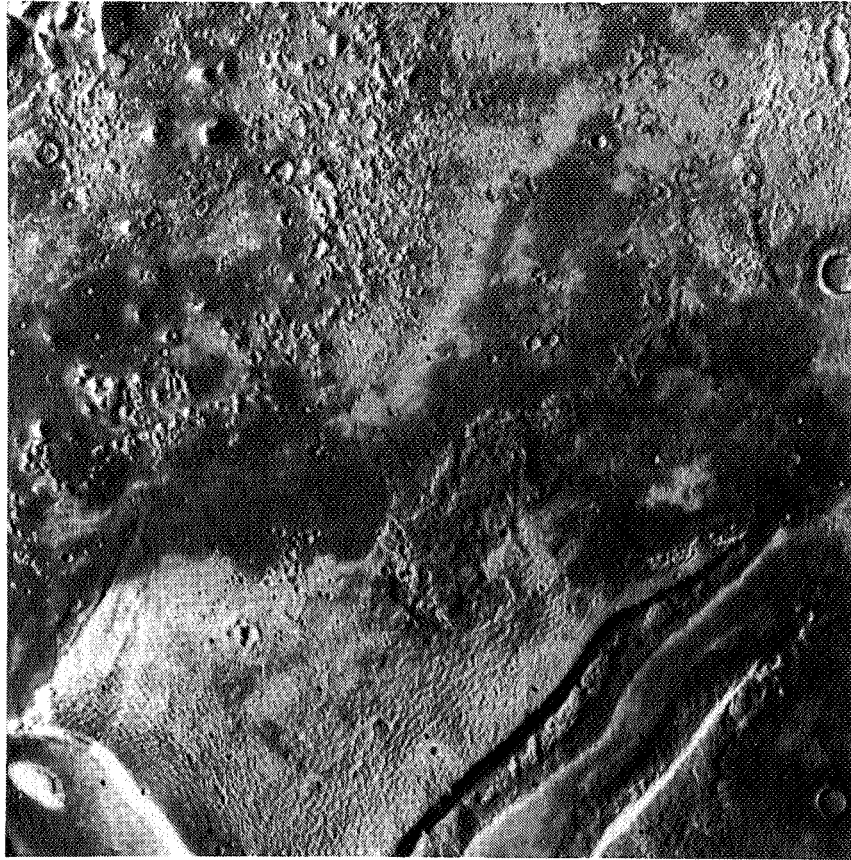
Study of the geology of other planetary bodies leads directly to a better understanding of the origin and evolution of the solar

system. There are two ways of attacking the problem: one is to model the evolution from an initially assumed state to the observed present condition; the other is to examine the present state of the solar system and deduce its history by moving backward in time. Both methods are valuable, but it is with the latter that the geologist is concerned. Generally, the surface of a planetary body preserves two records: one of its interactions with the external environment; the other is the result of processes intrinsic to the planet itself. Both records are fragmentary, and it is the task of the geologist to reconstruct the history of the planet from whatever record survives. This historical aspect of geology distinguishes it from many other disciplines, which usually are more concerned with characterizing and understanding the processes that are occurring at the present time.

The success with which the history of a planet can be deduced depends on how well the record is preserved and how clever one is in analyzing it. In the early stages of exploration, when only remote sensing data are available, emphasis is on interpretation of the topographic landforms and the spectral, photometric, and thermal properties of the surface. At a later stage of exploration, the record



*Jupiter's volcanic satellite Io in transit in front of the giant planet.*



*The complex geologic history of the martian surface is evident in this Viking Orbiter view.*

preserved in the petrology, mineralogy, and chemistry of the surface can be examined. For many objects in the solar system (Uranus, Neptune, Pluto, and their satellites, as well as for the asteroids and comets), not even the first of these two stages has begun. Only for Earth and the Moon has the second stage been reached.

The degree of preservation of the record varies from planet to planet and with it the extent to which the history of the planet can be reconstructed. On Mercury the record of interaction with the external environment is relatively well preserved because the cumulative effect of internal activity over the last 3 to 4 billion years has been small. In contrast, the topography of the volcanically active

satellite, Io, appears to result entirely from internal processes. Moreover, due to the intensity of the volcanism, the record of only relatively recent events is preserved. Fortunately, for most planetary bodies the record that survives covers a more extended period, and geologic histories can be reconstructed more fully.

Geophysics is concerned largely with documenting and interpreting structural heterogeneities and physical processes inside a planet. The chemistry of internal materials cannot be determined directly; nevertheless, inferences are possible from remotely measured physical properties. Although the value of any particular physical parameter may not be important in itself, its significance derives from the fact that it may provide information on internal chemical composition, conditions, and processes.

Stratigraphy is concerned with documentation of crustal heterogeneity. Even though surface rocks constitute a minute part of the total mass of the planet, it is the part most accessible to measurement. For this reason, an understanding of surface materials is crucial. We must know how variegated the surface rocks are and how they were formed. The mode and sequence of formation are particularly important, for different processes vary in timing and in the extent to which they cause chemical change. Consequently, to understand the broader implications of surface analyses, we should know the distribution and mode of formation of the rocks studied as well as the degree to which they typify the materials of the planet.

### ***1.1.2. Origin and Evolution of Life***

The geology of planetary surfaces bears directly on the origin of life in our solar system. Biologists concerned with understanding the evolution of life must know how a planet's environment has changed with time. This characterization includes a knowledge of the composition of rocks and minerals on and near the surface, the nature of the atmosphere and climate, and the nature and intensity of different geologic processes. These factors all involve aspects of planetary geology.

This report was written largely with the assumption that, in our solar system, life exists only on Earth, but that many important clues about the chemical precursors of life and the conditions necessary for life to evolve can be obtained by studying other solar system objects. Should life be found elsewhere, this strategy will



need drastic revision. Paleontology, which has been ignored in this strategy, would become a study of paramount importance, and different types of missions would be required to meet its needs.

### ***1.1.3. Our Terrestrial Environment***

An inevitable, important result of planetary exploration is an increased understanding of Earth. Many fundamental geologic problems are illuminated by detailed comparison of Earth with other planetary bodies. The relative effects of size and original composition and the presence of an atmosphere, hydrosphere, and biosphere on the evolution of Earth are of particular geologic importance; comparison of Earth with other bodies allows the importance of these effects to be assessed.

From the point of view of our terrestrial environment, the most significant results of planetary exploration will probably be an improved understanding of the early history and deep interior of Earth. Because the geologic record of events and processes that took place early in Earth's history has been largely destroyed by more recent events, very little is known of the first billion years of Earth's history. Features on Earth's surface are subject to relatively rapid destruction and modification as a result of the erosive action of water, and of tectonic and volcanic activity. Fortunately, the early histories of both the Moon and Mercury have been preserved on their surfaces, partly because both objects have been relatively inactive internally through much of geologic time, and partly because neither has an atmosphere, so that erosion rates have been much slower than those on Earth. The Moon and Mercury appear to have had similar early histories involving severe external bombardment, and there is growing evidence that this situation also extended to the other terrestrial planets, Mars, Venus, and Earth. It is not far-fetched to assert that the chances of understanding the development of continents and ocean basins on Earth are low if we do not understand the initial conditions which prevailed 4 billion years ago. An analysis of the geologic record preserved on the more primitive bodies may be the only way to arrive at an understanding of Earth's early history.

## **1.2. The Planetary Geology Approach**

How can the three objectives discussed above be met? In the geologic exploration of the solar system, certain basic questions can



be asked about any planet. These questions relate to the following: (1) the present geologic state of the planet, (2) how the present state differs from those that obtained in the past, and (3) how the planet's present and past geologic conditions differ from those of other solar system bodies.

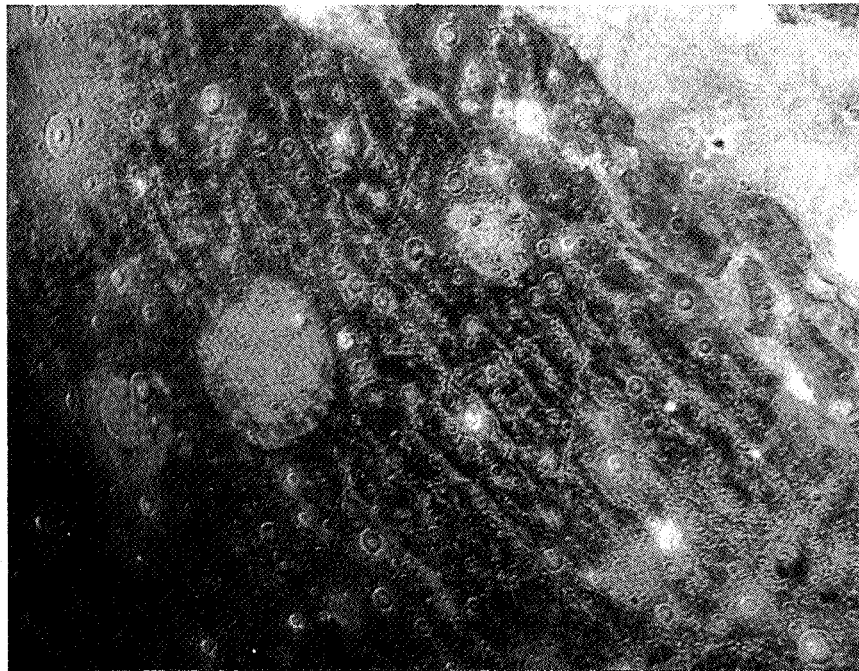
#### ***1.2.1. Present Geologic State***

The present state of a planet concerns knowledge of its surface morphology, the composition of the surface and interior, the physical nature of the interior, and whether or not there are active processes, such as volcanism. These topics are interrelated, and knowledge of one often provides clues to the others. Investigations of surface morphology involve the identification of the type and distribution of individual landforms, such as basins, mountain chains, and volcanoes, as well as structural elements such as fault scarps. The presence of these features often signals specific geologic processes. For example, the identification of volcanoes on Mars indicates melting in the interior, thus placing constraints on various models of the planet's internal structure and composition. Observations of variable surface features that can be related to specific eolian landforms suggest that wind processes play an important role in modifying the planet's surface. Determination of surface compositions and mapping of the distribution of rock types, as has been accomplished in part for the Moon, can provide direct information about the chemical differentiation of a planet.

#### ***1.2.2. Geological Evolution of Planets***

One of the primary goals in geology is to derive the geological history of a body, that is, to determine the sequence of events and processes that have occurred from the time of formation of the planet to the present. Specific questions about geological history include:

1. How have the various geologic processes, such as volcanism, tectonism, and erosion, varied through time in terms of type or magnitude, or both? For example, were there periods when impact cratering dominated?
2. Is there an imprint of earlier processes on the present surface morphology?
3. If the planet appears to be geochemically differentiated on a planetary scale, when and why did this differentiation occur?
4. How has the planet's interior evolved?



*The surface of Ganymede—the solar system's largest satellite. The large grey circular features are remnants of ancient craters that have been annealed by flow of the icy crust.*

5. How has the atmosphere evolved? Have there been significant variations in climate?

These profound questions are extremely difficult and, in some cases, probably impossible to answer completely. However, geochemical data, geologic mapping, and analyses of specific surface processes can provide important clues.

### **1.3. Comparative Planetology**

Comparative planetology is the study of the differences and similarities among planets and satellites. The last two decades have seen a tremendous expansion of knowledge of the inner solar system through successful lunar and planetary missions. We are beginning to perceive Earth as an extremely active planet with a thin lithosphere that slides over a plastic asthenosphere. At the other end of the activity scale is the Moon with its very thick, static lithosphere. With respect to many geologic processes, Mars has turned out to be more Earthlike, whereas Mercury shares many

attributes with the Moon. Venus, because of its dense cloud cover, remains largely unexplored; less is known about its present state and evolution than about any other Earthlike planet.

Earth, its Moon, and the meteorites remain important reference points for comparative studies in planetology and will continue to be for the foreseeable future. A much more comprehensive set of basic data is available for Earth than for any other object. As a highly differentiated object that possesses a core, mantle, and crust, and whose internal thermally driven processes are still active, Earth is a natural laboratory for investigation of these processes. The Moon is the only body sampled and studied in detail on which particles and radiation interact directly with the surface without the shielding of an intervening atmosphere. The Moon also represents a body in a stage of planetary evolution different from that of Earth and one which, in terms of size, is similar to an important class of objects that includes Mercury and many of the satellites of the giant planets.

Meteorites supply the greatest variety of "returned samples" from the solar system and provide important clues about the very early conditions and processes in the solar nebula, variations in chemical composition among solid objects, and the lifetimes and collision frequency of planetary debris. Experience in studying the Earth, Moon, and meteorites has highlighted the fact that one measurement, or even one set of data, may not yield answers to the major questions associated with the formation and evolution of these objects. Many types of data must be obtained to understand the important processes active in the formation, evolution, and present state of each object in the solar system as well as that of the solar system itself. These data include global surveys from spacecraft, analyses of returned samples, and the results of theoretical modeling, laboratory experiments, and investigation of specific features on Earth that may provide clues about geologic processes on other bodies.

The chapters that follow describe the major aspects of planetary geology and discuss means of obtaining relevant data. It is not our intention to assess the relative merits of various instruments that could be employed on future planetary missions, but rather to present the types of measurements that should be made and to discuss their relevance to answering fundamental questions about our solar system.

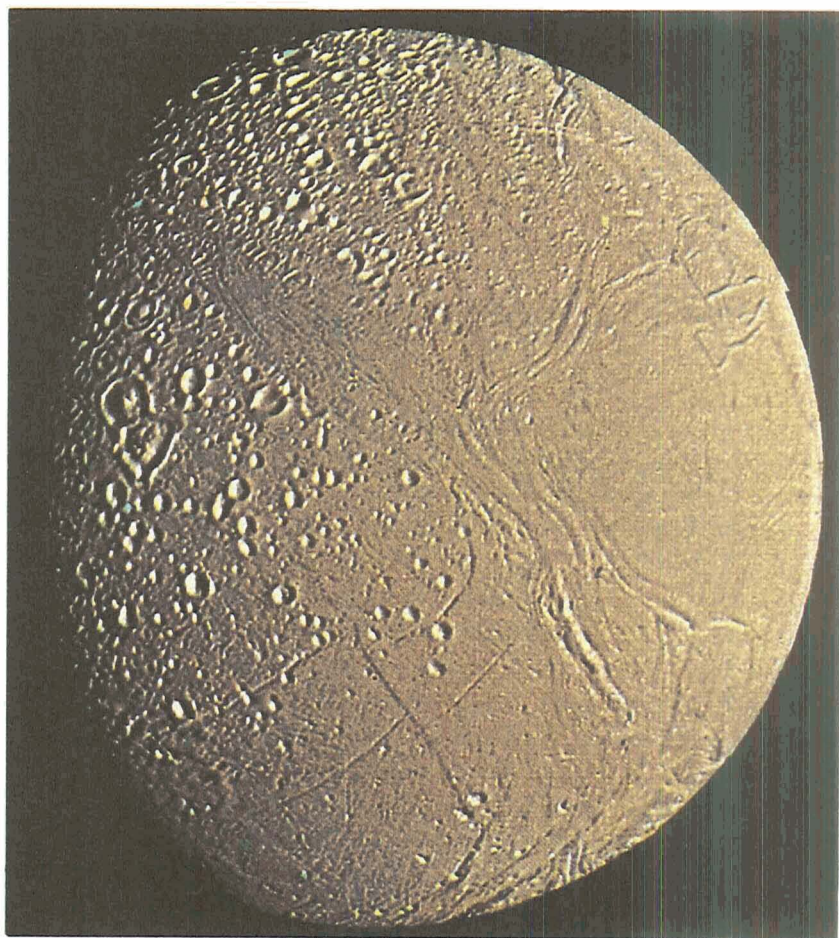
## **2 Surface Features and Processes**

The term geology literally means the study of Earth, but the discipline normally concentrates on Earth's surface and near surface because these are the most accessible parts of the planet. Through the examination of the nature and disposition of surface rocks we attempt to reconstruct how Earth formed and how it has evolved to its present state. Since the beginning of space exploration two decades ago, the term geology has assumed a broader meaning and includes the study of solid planets, as well as the satellites, asteroids, and comets of the solar system. The emphasis is still on surface studies, since, as in the case of Earth, the surfaces are the only parts accessible to direct observation. Planetary geology attempts to reconstruct the evolution of planetary bodies, largely from the fragmentary records that have survived on their surfaces.

The evolution of any planet or satellite is in large part controlled by initial conditions such as size, bulk chemistry, and distance from the Sun. The object's surface is subject to a variety of processes which fall into three broad categories:

1. Deep-seated, internally driven processes, such as tectonism and volcanism.
2. Surficial processes, normally involving the interaction of the surface with the atmosphere or hydrosphere. Examples include mass wasting, fluvial erosion, and eolian transport.
3. External processes, such as impact cratering and interactions with the solar wind.

Surfaces in the solar system tend to have complex configurations, reflecting intricate histories of the interaction of a variety of processes. Not only do different processes dominate on different



*Saturn's icy satellite Enceladus: the roles of both internal and external geologic processes are evident on its surface.*

bodies, but their relative importance on a particular planet or satellite may have changed with time. The Moon provides a familiar example: impacts dominated until some 3.9 billion years ago, from which point until 3.2 billion years ago, volcanic processes responsible for the formation of the mare prevailed. Since that time, as volcanism declined, impact processes again became dominant on the Moon. On Mars, geologic evolution was more complex. There it seems that volcanism, tectonism, impact cratering, eolian and fluvial activity, as well as other processes, were significant throughout the planet's history. The geologist's task is to reconstruct from the

fragmentary record that is preserved what processes have shaped the planet's surface and what their relative roles have been as a function of time.

In the sections that follow, important geologic processes are discussed individually, and specific recommendations are made that will lead to a better understanding of their roles in the evolution of planetary and satellite surfaces. The different studies are clearly interrelated. Silicate magmas may react with ground water, impacts may induce volcanism, tectonic features are subject to mass wasting, etc. In addition, different processes can produce similar landforms; for example, both volcanism and fluvial processes can produce channels. Only by studying the whole range of geologic processes and phenomena that might affect a planet can we hope to arrive at a secure interpretation.

## **2.1. Structural Geology and Tectonics**

Unraveling the deformational history of planetary bodies involves the application of the methods of both structural geology and tectonics. The two fields ask related questions but differ in the scale of phenomena they treat. Structural geology deals with local deformational features such as faults and folds, the local stress fields which caused them, the timing and sequence of events within these local structures, and the mechanisms by which they operated. As the size of the region expands from the subcontinental to global, the term structural geology gives way to tectonics. The word tectonics springs from Greek roots meaning framework and denotes the concern of that discipline for the broader framework of deformational and geologic history into which individual local events are to be fitted. This tectonic overview of a planet combines structural data with those of geophysics, geochemistry, and a variety of types of age determination to build a conceptual model of the global planetary machine in terms of geometry, mechanics, and energy sources that have powered it through its various evolutionary stages.

### ***2.1.1. Basic Questions***

The kinds of local questions structural geology might ask include:

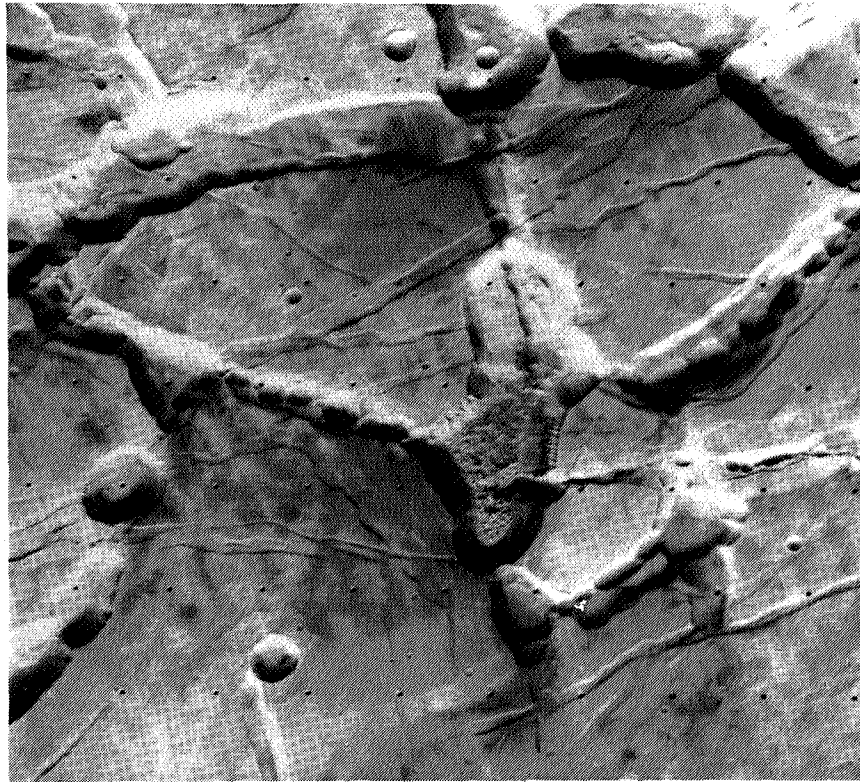
1. What stress orientation and magnitudes were necessary in a given area to produce an observed fault, fracture, or fold

- pattern? Has the area been extended or compressed? By how much? In what directions? Did this involve multiple deformations? Were the motions dominantly vertical or horizontal? What were the magnitudes of the displacements?
2. To what extent did the anisotropy of preexisting structures influence the development of younger structural features?
  3. What other features or processes, such as impact basins, drainage patterns, volcanism, stratigraphic changes, or erosional cycles, were linked to the observed structural features in terms of time and/or geometry?
  4. What is the mechanical character, strength, viscosity, thickness, etc., of the rock units comprising the area? How deeply are the rock units being affected by these structural processes? Were they deformed dominantly by viscous or ductile means or by brittle failure? What stress magnitudes were required?
  5. What was the relative timing of the sequence of events in the area? To what extent can these relative ages be linked to radiometric age dates?

Tectonics may ask many of the same questions but in a more global context. Most of these questions are closely intertwined with data and problems dealt with in geophysics and geochemistry:

1. Do the observed structures link into patterns indicating broad regions or tectonic provinces that have had a generally similar structural and geologic history? If so, what overall mechanisms were responsible for these relationships?
2. To what extent have these regions come to an isostatic or floating equilibrium as revealed by gravity data? What depths mark the transition from ductile to brittle deformation? What stress magnitudes are produced at these depths? Have these characteristics changed as a function of time?
3. Has the planet as a whole been contracting or expanding through time? Has this behavior changed through time? If so, when?
4. Is there any relationship of the overall deformational patterns and history to planetary asymmetry, to loading by polar deposits, or to changes in planetary shape reflecting changes in rate of rotation?
5. Can the energy budget of the planet over geologic time be





*A hint of the complex tectonic evolution of Mars.*

reconciled with its total chemical evolution to produce the sequence and types of geologic units and structures observed?

Thus, tectonics seeks to determine the models that can explain the sequence and timing of development of the first-order features of a planetary body, including the local details derived from structural geology. This is the ultimate goal of tectonics: to determine an overall model of the way a planet has evolved.

### ***2.1.2. Geologic Maps***

More than most other subdisciplines of the geosciences structural geology and tectonics involve relating surface observations to depth and time. Among the most important tools for making these links is the geologic map, a graphic representation of the distribution of rock units and structural features with indications of their



vertical and age relationships. It is through the careful production of such maps that the details of the geologic history of a body are worked out. Their production requires much more than the mere tracing of areas of similar landforms onto a map. The three-dimensional relationships, as well as the time sequence of events, must be linked into a logical sequence. Surficial processes must be understood in enough detail to recognize how they create the landforms, redistribute materials, and mark surfaces of different ages. Various types of multispectral images can provide valuable information on distribution of rock and mineral types. Geophysical observations can give clues of subsurface boundaries and characteristics.

Ultimately, the subsurface of a planet must be linked with its surface characteristics either by geophysical techniques or by some surface phenomena that connect the two levels. The most common of these links are volcanic deposits and structural features. By means of cratering, degradation of topography, or superposition, the volcanic deposits are usually dated more easily than fault or fold structures; on the other hand, the structural features give more unique indications of stress type and orientation. Both types of information are embedded in the geologic maps and represent an outline of events that the tectonic model must explain. The geologic maps constitute the base on which the bulk of geologic observations about a planet must be placed; they must be upgraded as geologic understanding of a planet increases. At any point in time the best current geologic map represents the major detailed data base the tectonic model seeks to explain.

### ***2.1.3. Experimental Stress/Strain Studies***

Much of the focus of structural geology and tectonics is on the magnitude and character of present and past stress fields. Unfortunately, the present stress field is essentially unobservable except by the strains it produces; past stress fields are even more enigmatic. Thus, the process becomes one of recording or mapping the complex strains that have been imposed on the rocks and interpreting or deducing the stresses that caused them. Furthermore, many of these strains were produced at depths and temperatures at which the mechanical characteristics of even Earth materials are poorly known, adding a complication to the interpretation.

Over the last half century a massive body of experimental data on the mechanical properties of most ordinary rocks and minerals

has been accumulated. This includes stress to strain relationships under many conditions, including those in the deep interior of Earth and in the presence of a variety of volatiles. The internal glide and recrystallization mechanisms utilized by many minerals are reasonably well known. The yield and breaking strengths of many rocks are well documented, as are their effective viscous behaviors under long-term loading.

The recent recognition and better definition of volatile-rich solid planetary bodies in the outer solar system necessitate an improved data base for relating stress to strain on such objects. Although we can handle many of the deformation problems of ordinary rocks, improving the structural/tectonic analyses of the more exotic bodies of the outer solar system requires a significant expansion of the rock mechanics data base to include volatile-rich materials as well as compositions far different from the traditional silicates that dominate so much of the chemistry of the inner solar system.

#### ***2.1.4. Stress Field Indicators***

On Earth, the modern or present-day stress fields are determined by detailed observations and measurements of their effects. Precise measurements across active fault or fold zones give indications of both horizontal and vertical displacements produced by the stress. The pattern of seismic energy release in a quake can be related to the magnitude of stress drop in the fault that produced that event. Compressional or extensional displacement patterns of seismographs by first motions of an earthquake define the orientation of the stress field causing the quake. Strain gauges used in drilling operations record the expansion of rocks as they are removed from their confining stress and hence indicate the magnitude and orientation of that stress. Fracture operations associated with oil fields break rocks by excess pressures in drill holes, the magnitude of overpressure required for breakage being an indication of the stress at depth and the fracture orientation being related to the stress orientation. These methods, although highly useful on Earth, cannot be applied at present to other planets.

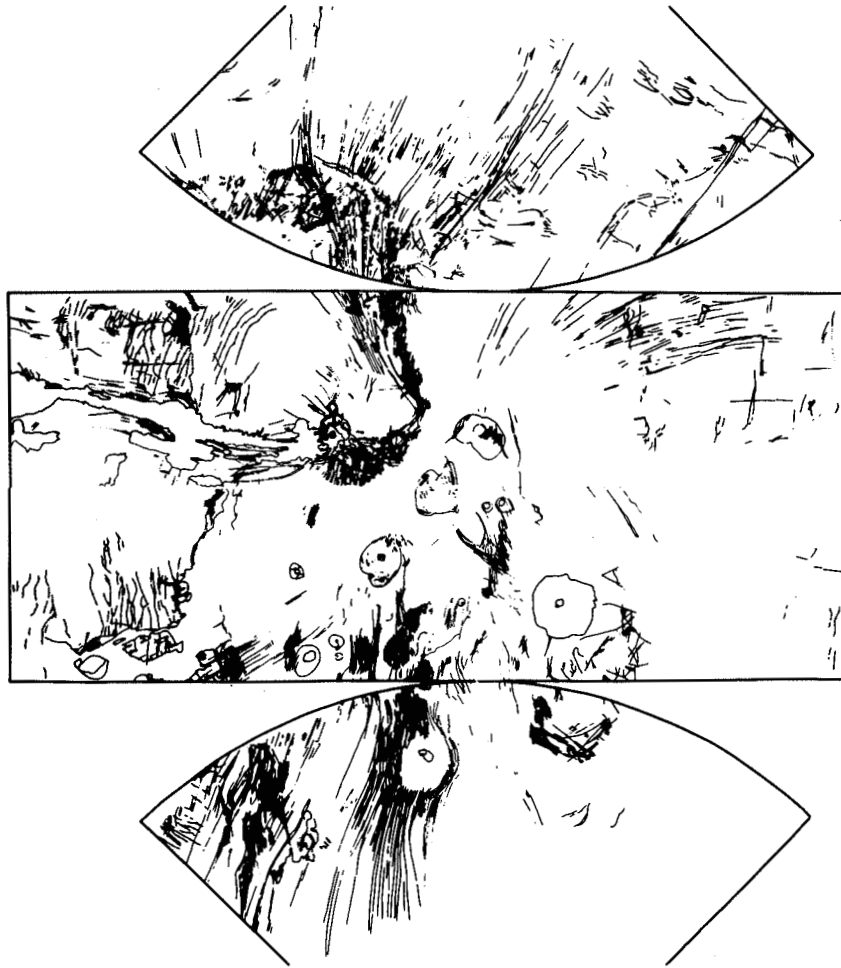
On Earth, fault systems are widely used as paleostress field indicators. As noted by Anderson (1951), the free surface of Earth is a plane of no shear; hence, one of the three principal stresses should be approximately vertical at any location on the surface of our planet. If the maximum compressive stress is vertical, a system

of normal faults should result, with the strike of the faults parallel to the intermediate principal stress. If the minimum compressive stress is vertical, a system of thrust faults should result, with the faults striking parallel to the intermediate principal stress. If the intermediate principal stress is vertical, a paired system of strike slip faults should develop, with the maximum compressive stress as their acute bisector. Anderson further expanded his model to point out that dikes or other swarms of fracture filling should open perpendicular to the least compressive stress direction.

Many other indications of paleostress orientation or magnitude are available on our planet. Most surficial fold systems indicate compression approximately perpendicular to the trend of the folds; the wavelengths of the folds are related to viscosity contrasts in the folding materials. A host of outcrop and microscopic-scale strain indicators are utilized for terrestrial deformation analyses, including mineral twins, kink zones, veins, and planes of recrystallization. At the present stage of exploration, such indicators have little applicability to other planets.

For other bodies, the most valuable stress/strain indicators are fault systems viewed in the context of Anderson's ideas (e.g., Plescia and Saunders, 1982; McKinnon and Melosh, 1980). Strain markers in the form of originally straight-line or originally circular crater outlines can be utilized to measure the magnitude of strain. Other patterns of fractures of radial or concentric nature may indicate stress concentrations about some center. Arrays of fractures in formation or in echelon to each other can indicate lateral displacement along buried fracture zones. These surficial indicators of deeper stress must be used with caution because preexisting weaknesses or earlier fracture systems may influence the orientations of younger fractures.

Among the most widespread and least understood of all paleostress indicators are large-scale fracture traces or lineaments etched by erosion into the topography of almost all areas of Earth and readily visible on Landsat and Seasat images (Wise and Allison, 1981). Similar linear features appear on almost all solid bodies of the solar system imaged to date and have been the basis of proposed "lunar grids," "martian grids," and "mercurian grids." It is generally agreed that these represent some type of fracture traces related in some way to stress systems, but the exact relationships remain hotly debated. As a ubiquitous topographic element, these linear features have considerable potential for determining the



*Deformational features in the vicinity of the Tharsis bulge on Mars mapped by J. Plescia (from Carr, 1981).*

stress history of planetary surfaces. Unfortunately, at present this potential cannot be realized. The reproducibility of the lines drawn by different observers is questionable. Furthermore, there is no agreement on the statistical methodology that should be used to treat such data, and the origin of the linear features on Earth is not clear.

#### **2.1.5. Tectonic Energy and the Generation of Stress Fields**

Identification of the timing and character of past or present stress fields is an intermediate step in understanding the geologic

history of a planet (e.g., Wise et al., 1979). Ultimately, the causes of the stress fields must be related to an overall geologic and tectonic model and to the sources of energy that power that model.

On Earth, the driving forces of plate tectonics and the associated stress fields are believed to involve the sinking of ocean plates as they cool and grow denser at subduction zones, as well as the sliding of plates off upraised, less dense, hotter ridges of oceanic mantle material. To the extent that the density contrasts are thermally driven, this process is a form of convection, even though the mantle is a relatively passive element in the system. Other ideas of the driving process include large, thick cells of deep mantle actively overturning and convective mantle plumes dragging passive surface materials along on their tops. The relative importance of these various processes on Earth today is uncertain; their importance at times past, especially on other planets, is even more uncertain.

Many other processes can generate stress fields on regional or planetary scales. Impacting bodies create intense but short-lived stress fields. Internal temperature changes associated with the decay of radioactive elements, core formation, etc., can lead to expansion or contraction at differing depths. Volumetric changes associated with permafrost regions of Mars probably account for many local fractures. Changes in surface or subsurface loading can be produced by volcanic piles, polar deposits, erosion at surficial or subcrustal depths, or lateral magmatic movements. Gravitational sliding of surface materials from topographic highs creates many local stresses. Any load not supported by isostatic equilibrium must be supported by stresses maintained by the strength of the planet; for example, the lunar mascons create strong local stress fields in their immediate vicinity. Even in isostatic equilibrium, differences in density at the same depths in adjacent columns will cause stress differences. Tidal torques can stress surfaces and change rotation rates. "Despinning" of planets alters their oblatenesses, expanding their polar crustal regions, compressing the equatorial regions, and deforming the middle latitudes by shear.

#### **2.1.6. Methodology**

The development of structural and tectonic models of planetary bodies progresses through several stages. Initially, the level of tectonic and surface activity for any newly imaged planetary body is estimated from the relative abundance of surviving craters versus

structurally or erosionally produced features. Basic planimetric and topographic maps are produced. At this stage, the major topographic and structural features are classified and located in a general way, and tentative mechanisms for their origin are proposed. Examples might include fault troughs, volcanic features, lineaments, wrinkle ridges, etc. In addition, the first-order geologic provinces are defined and crudely mapped based on the distribution of these features. Subsequent stages of the exploration involve detailed geologic mapping closely linking surface characteristics, topography, structural and geomorphic features, unconformities, and age indicators into a relative sequence of events. The mapping is supplemented by many types of geochemical, geophysical, and remote sensing data. More detailed relative age distinctions are made based on crater densities; age correlations related to these densities also may be attempted from region to region. Based on models of the cratering history in the solar system, these cratering ages may be linked to the more traditional time scales derived from radioactive decay (chapter 3).

From this set of data, the broad outline of the planet's history is developed, including the cratering history, stress history, and volcanic history. If possible, limits on the atmospheric and volatile evolution are determined. Some idea of the density structure and layering may be deduced from the figure of the planet, isostatic considerations, and crustal flexures. In general, these multiple approaches to the planet's history are mutually supportive, constraining each other and suggesting which geologic processes and mechanisms are most important. Usually the result is a second generation of improved geologic mapping, more sophisticated geologic process studies, better stress orientation determinations, and improved timing of events. At this stage, it becomes possible to formulate working tectonic models, to test the physical plausibility of these models, and to judge their implications for creating the details of the observed geologic surface of the planet and its associated internal characteristics.

#### ***2.1.7. Summary***

A major long-term goal of our planetary exploration program should be the development of tectonic models of all the solid bodies of the solar system. This task would involve working out the detailed structural and geologic history of the bodies, combining

these with geophysical and geochemical observations to provide tectonic constraints as the basis for each model. From these models, general principles of planetary behavior and evolution should become much clearer and illuminate much more fully the history and mechanisms of Earth's evolution.

Standard geologic mapping is a vital foundation to understanding the nature and evolution of any planetary body. The use of multispectral and other remote sensing maps to supplement the standard geologic maps should be exploited more fully.

Intriguing linear patterns exist on all the solid planets imaged to date. It is likely that they constitute important hints to the past stress history of the bodies, but our ability to understand and interpret them is limited at best. There is ample room for much more sophisticated work in this area.

The mechanics of icy planets are understood very poorly. Even the basic physical and deformational properties of many candidate materials for these planets are precisely known. A major effort is needed in these areas if the results of exploration of the outer solar system are to be interpreted properly and fully.

## **2.2. Volcanism**

Volcanic landforms provide some of the clearest evidence for how a planet has evolved. They give clues concerning thermal conditions in the interior, the composition of the mantle, and the structure of the lithosphere; if the landforms can be dated, then changes in these characteristics can be traced through time. The landforms also provide clues to the style of volcanism and to the composition and physical properties of the materials involved. Because of the applicability to Mars and the Moon, studies of planetary volcanism during the 1970s tended to focus on activity involving the eruption of large amounts of fluid lava (Carr, 1973; Carr et al., 1977; Greeley, 1976; Carr and Greeley, 1980). However, with acquisition of broader photographic coverage of Mars and following the Voyager encounters with Jupiter and Saturn, we have been confronted with a wide array of volcanic features, the products of various types of volcanism. Io appears to erupt lavas of sulfur (Schaber, 1980), the surfaces of Europa and Ganymede appear to have been modified by the eruption of ice-rich materials (Smith et al., 1979b), and interaction of silicate magmas with ice and ground water may have been important in producing various landforms on Mars (Carr, 1981). Planetary volcanic studies must therefore be

broadened considerably in scope if we are to achieve a better understanding of these bodies. Inevitably, the shift in emphasis will bring a change in the style in which the study of planetary volcanism is pursued. In the past, considerable reliance has been placed on comparisons among the planets, particularly with Earth, where some volcanic processes are reasonably well understood. These comparisons have been largely geomorphologic. As more exotic types of volcanism are encountered, simple comparisons become less appropriate and we expect greater reliance on theoretical studies and experimental work to extrapolate from our terrestrial experience while still acknowledging the need for analog studies where possible to test the modeling work.

### ***2.2.1. Geomorphology of Volcanic Landforms***

Geomorphology is an important basis for almost all planetary volcanic studies; observation of landforms leads directly to examination of different volcanic mechanisms; and all the theoretical and experimental studies must ultimately be reconciled with what is actually observed. The most straightforward geomorphologic studies involve comparison of landforms seen on other planets with those formed on Earth by known processes. Leveed channels, lobate flow fronts, and lines of "skylights" over a lava tube, for example, all suggest eruption of fluid lavas, whereas steeply sloping cones are more indicative of explosive activity. Such comparisons have proven extremely useful in leading to a better understanding of planetary volcanism and in fact are the basis for much of our present knowledge of other planets.

To facilitate comparative studies, extensive documentation is needed of volcanic landforms on Earth and other bodies. We need a comprehensive collection of satellite images of Earth's volcanic fields at scales similar to those obtained from the other planets. Moreover, we need quantitative measures of volcano heights, diameters of vents and edifices, depths of calderas, flow thicknesses, and so forth. Such data not only would allow more precise comparisons to be made (taking into account the different planetary environments), but are essential for testing theoretical models of various volcanic processes and for assessment of the physical properties of the materials involved.

Although volcanic processes occur on other planets under conditions vastly different from those on Earth, and with magmas of radically different compositions, comparison of extraterrestrial and





*The martian volcano Ceranius Tholus.*

terrestrial volcanic features must still be an essential element in any program of planetary studies. If nothing else, analog studies demonstrate the complexity of volcanic processes and emphasize the enormous gap between idealized models and reality. Often analog studies also suggest possible explanations for features seen on other planets and provide a means of testing theory. Studies should include a broad array of volcanic features such as those formed by subglacial eruptions, by phreatic phenomena, or by magmas of exotic compositions. Detailed investigations of how volcanic landforms evolve should be included, for often the ultimate form is the result of a complex sequence of events that is not obvious from a cursory examination of the final configuration. The growth of Mauna Ulu, Hawaii, for example, consisted of a complicated sequence of events involving the repeated formation and drainage of underground lava reservoirs, development of ancillary vents and lava tube systems, and repeated growth and partial filling of the main vent.

The icy satellites of Jupiter and Saturn present an unusual challenge. Europa, Ganymede, Enceladus, and possibly others appear to have been resurfaced by eruptions of ice from the interior (Smith et al., 1979b, 1981). Whether this process should be called volcanism could be debated, but it does involve the eruption of a relatively warm and mobile fluid from the interior of the body onto a cooler surface. Terrestrial analogs for such features should be sought.

#### ***2.2.2. Modeling of Volcanic Processes***

Because volcanism on other planets take place under conditions vastly different from those on Earth, an understanding of these processes is unlikely to follow from simple comparison of the resulting landforms; theoretical work is needed to determine how the processes are affected by the different environments. For example, low gravity and the absence of an atmosphere might result in different disposition of volcanic products around a vent; the dimension of lava flows may vary in a predictable way with rheologic properties and eruption rates, and volcano heights may give an indication of lithosphere thickness. Evaluation of such effects requires that the processes be modeled and that they be described in some analytical way so that the effects of changing different variables can be assessed.

It is inappropriate here to suggest a comprehensive list of specific topics for research; these will become evident as the field advances and as specific gaps in our understanding begin to hinder further progress. However, the types of theoretical studies that certainly should be pursued include:

1. Modeling the physics of movement of magma to the surface, taking into account density differences between magma and host rock, viscous heat loss, and so forth. Such studies are essential for assessing lithospheric thickness from volcano dimensions and may provide important clues to causes of periodicity in volcanism.
2. Understanding the physics of gas-rich eruptions as appropriate for Io, Mars, and other bodies. Pioneering work has already been done in this area, particularly by Smith et al. (1979a), Cook et al. (1979), Sparks (1978), Sparks et al. (1978), and Kieffer (1982), but considerably more effort is required.
3. Knowledge of the physics of emplacement of lava flows is essential for understanding the vast flow fields of the Moon, Mars, and Io, yet only limited work has been accomplished in the field (Shaw and Swanson, 1970; Hulme, 1974). We need far more information on how rheologic properties and eruption rates affect flow dimensions and how the rheologic properties are related to lava composition, temperature, volatile contents, and so forth.
4. The causes of periodicity in volcanic eruptions remain largely unknown. Eruptions of the large martian volcanoes appear to be separated by long periods of inactivity, Ionian volcanism appears to be periodic with short time scales, and most terrestrial volcanism appears to be somewhere between. The models of Joly (1930) and Cotter (1924) and their applicability to different planets should be explored.
5. We have considerable information on caldera dimensions on other planets, but how caldera dimensions relate to the depth and diameter of near-surface magma chambers or the inflation-deflation cycle is unknown. Modeling of caldera formation could lead to a better understanding of the structure of the crust beneath the many calderas observed on planetary bodies.

These suggestions provide examples of the types of theoretical work that would be useful for a better understanding of volcanic processes on other planets. It should be reemphasized that such work must be done in close conjunction with studies of terrestrial volcanoes so that the theory can be tested. Experimental data may also be needed to support the theory in many cases, for example, in relating flow morphology to rheologic properties.

### ***2.2.3. Experimental Petrology***

Perhaps one of the largest gaps in our understanding of planetary volcanism is in the area of petrogenesis. Most of the experimental work on silicate melts has been done on systems that are appropriate for terrestrial conditions. Almost no work, for example, has been done on extremely sulfur-rich or ice-rich systems that might be more appropriate for the satellites of the outer planets.

Experimental petrology is the laboratory investigation of chemical systems thought appropriate to the understanding of petrogenesis. This effort involves the study of chemical systems much simplified over natural ones as well as direct experimentation on representative natural samples. The goal of experimental petrology is generally elucidation of (1) the physiochemical conditions under which a rock formed, these being temperature, total pressure, fugacities of the various participating gaseous species, and activities of other components in the system, and (2) the specific reactions and reaction paths actually followed in rock formation. This goal is accomplished by duplicating, in heated pressurized vessels, the assemblage of minerals found significant in a particular natural setting. The value of experimental petrology thus lies precisely in the fact that it quantifies petrology.

Important contributions provided by experimental petrology to understanding the planet Earth include:

1. Definition of the pressure-temperature (P-T) fields of stability of common and diagnostic crustal mineral assemblages. This work has allowed metamorphic petrology to advance beyond the concepts of isograds and facies to include facies series (Miyashiro, 1961; Hewitt and Gilbert, 1975). The same approach is being extended to higher-pressure assemblages thought characteristic of the upper mantle (MacGregor, 1970).

2. Implicit in (1) is that the paleogeothermal gradient for a terrain can be estimated. Once this is known, tectonic models and thermal profiles of the upper mantle can be derived (Richardson, 1970; Boyd, 1973).
3. Mantle compositions have been inferred from partial melting experiments on various bulk compositions until liquids matching the range of natural lava types were obtained. These results have also allowed determination of (a) the effect of different volatile constituents on melting behavior and (b) the fractionation of elements such as K, U, and Th between the participating solid phases and liquid. The measured silicate melting curves are used to place constraints on the thermal state of Earth's interior. Thus, the general processes of formation of differentiated crust, ocean, and atmosphere can now be quantitatively modeled (Boettcher, 1975).
4. All common rock-forming minerals of Earth's crust undergo transformations to denser forms at high pressure. Only through laboratory experimentation can petrology and geophysics be merged into viable models of Earth structure and chemistry (Ringwood, 1970), making it possible to relate seismically defined discontinuities to possible chemical and physical changes.
5. Lava viscosities affect the form of volcanic edifices, and viscosity is a direct function of chemistry.

In principle, all the points outlined are applicable to the terrestrial planets and to rocky satellites of the Jovian planets. The crucial question is, to what extent can information from laboratory studies of chemical systems be applied to other planets? This question involves estimations of both the relevant bulk compositions and the appropriate physical conditions. It seems clear that much additional work will be necessary simply because evidence is abundant that bulk compositions are different from one planetary body to the next. Highly oxidizing conditions have rarely been investigated for Earth materials at high temperatures and pressures because such conditions were not applicable here. Yet such studies may be appropriate for other planets. In a similar vein, highly reducing conditions were not investigated before the advent of lunar studies, as there was no immediate reason to do so. On the other hand, a substantial body of phase equilibrium data exists for many common

minerals. Wherever these data have been determined for a wide range of physical conditions, they will probably be useful in planetary geology.

For Mercury, an important question in view of the existence of an internal magnetic field is whether the planet has a liquid core. Bulk geochemistry as inferred from some formation models points toward a sulfur-free, iron-rich core. The pressure at the core-mantle boundary should be about 60 kbar. In the absence of sulfur, temperatures would have to be above 1600°C for the core to melt. However, if sulfur were present, a liquid outer core could be maintained at only ~1000°C. Thus, thermal and differentiation models are critically dependent on the bulk composition chosen. A mantle silicate chemistry rich in Ca and Mg and low in Fe would imply very high melting temperatures.

For Mars, some geochemical models imply a high sulfur content (see also Clark et al., 1976). Thus, a liquid core could be maintained at moderate temperatures. On the other hand, the basalt melting interval may not be appropriate because of the possibility of a higher oxidation state for the planet. If the higher oxidation state hypothesis were true, other consequences follow; Higgins and Gilbert (1973) have argued that nickel will then be released into the silicate system and be housed in the "ferromagnesian" minerals. Significant changes in melting temperatures, element fractionation, and phase stability are then possible. Since it is often postulated that the volatile content of Mars exceeds that of Earth, much of this theory might turn out to be inappropriate, in which case other studies (e.g., Eggler, 1974) might be more pertinent.

#### **2.2.4. Summary**

During the past decade, planetary volcanic studies have focused on features formed by eruption of fluid basaltic lava because of their importance on the Moon and Mars. Recently, however, we have been confronted with a variety of volcanic features on Mars and the satellites of the outer planets that have been produced by other forms of volcanism. Planetary volcanic studies should accordingly broaden in scope to include the full range of volcanic phenomena encountered on Earth, as well as volcanic processes that might occur on other bodies through eruption of magmas of exotic compositions, such as sulfur and ice. Study of terrestrial analogs,

modeling of volcanic phenomena, and theoretical and experimental work on appropriate chemical systems should all proceed vigorously in concert.

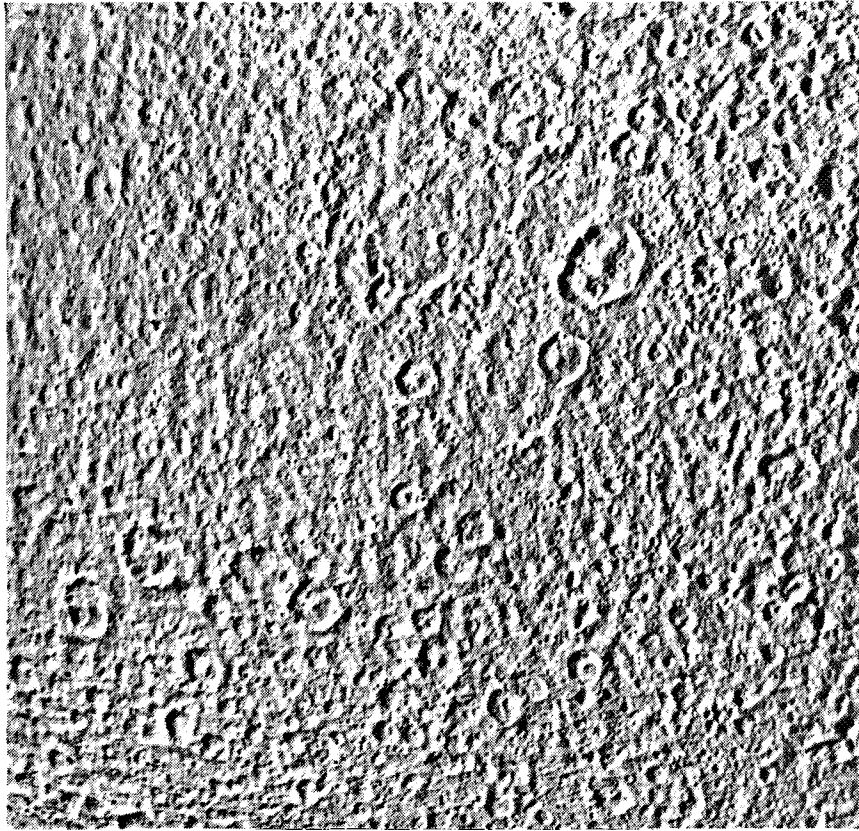
### **2.3. Cratering**

Cratering has been a ubiquitous process in the solar system since its formation. After some initial debate, a consensus has been reached that most of the craters seen on the surfaces of the Moon and the planets were formed by hypervelocity impacts of cosmic debris. Although the earliest work focused on using these features to estimate the relative ages of surface units, more recent studies have concentrated on understanding the cratering process itself. Whereas many of these investigations have dealt with impacts into rocky surfaces, spacecraft investigations of Mars and the satellites of the outer planets have demonstrated the importance of extending such studies to other target materials, including ice-rich regoliths and pure ice.

#### ***2.3.1. Impact Cratering: An Introduction***

A hypervelocity impact results in two shock fronts, one of which propagates into the target and the other into the projectile. The shock front in the target compresses the material comprising the medium, setting it in motion and, provided the resulting stresses are sufficiently large, causing changes in its physical state (e.g., from solid to liquid or vapor, or combinations of the two). Decompression of the stressed, moving material alters the "flow field" initiated by the shock, inducing ejection of target material from a growing cavity and rebound of the target medium that was compressed more or less in situ. The end results are a hole in the ground (the crater) and a surrounding deposit of ejecta.

The final shape of the crater is determined by a number of factors, among which are the surface gravity and size of the target body, the physical and chemical properties of the target and projectile, the size, velocity, and angle of impact of the projectile, and the ambient atmospheric pressure. These parameters will also govern the characteristics of the crater's ejecta deposit. As the magnitude of the impact increases, elastic properties of deep-seated material and the gravitational field and size of the target body generally become more important in governing the outcome of a cratering event, while the effects of target strength, angle of impact, and



*The heavily cratered surface of Saturn's icy satellite Rhea.*

atmospheric pressure decrease. Thus, elastic and gravitational mechanisms modify crater cavities more intensely as larger craters are considered; indeed, the increase in crater complexity with size has been well documented on all cratered surfaces studied to date. Very large craters usually possess morphologies characterized by multiple, concentric rings and, depending on the number of such rings, are called peak-ring or multiring basins. The diameters of these structures range from  $\sim 100$  km to over 2000 km, implying that their formation affected the target bodies on truly gigantic scales.

The average changes in crater shape and appearance with increasing diameter are firmly established (e.g., Hartmann, 1972b, 1973); the reasons for these trends, however, are not fully understood. A precise assessment of the relative importance of the major



variables mentioned above and of the specific roles they play in determining the observed variation in crater morphology with size remains a fundamental goal of crater research (Roddy et al., 1977).

### **2.3.2. Methods of Study**

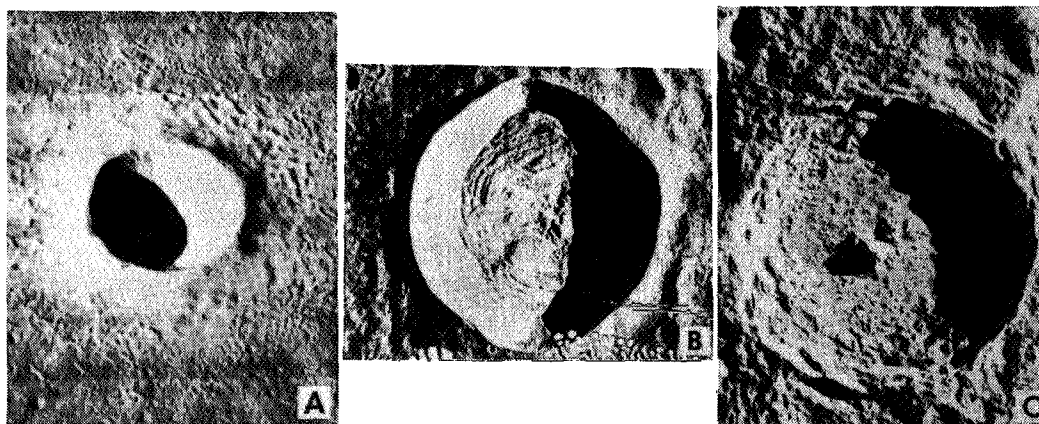
Craters can be studied by a variety of methods, but in general the most valuable results are achieved by combinations of complementary techniques. The most important of these include:

*Spacecraft Imaging.* Cameras carried by spacecraft allow the examination of craters spanning a vast size range and a wide spectrum of degradational states in their natural settings. Such observations provide data from which topographic, morphologic, and other information can be derived. Comparison of craters on different planets permits an assessment of the effects of varying parameters, such as surface gravity, target properties, and average impact velocity.

*Field Observations.* Detailed descriptions of target stratigraphy coupled with subsurface structural information are perhaps the most valuable results of in situ field work. Petrologic, petrographic, and other geochemical data from impact sites are exceedingly useful in analyzing the propagation and effects of impact-generated shocks. Geophysical measurements—such as those obtained by gravity and magnetic surveys—yield information about deep crater structure and bulk target response to the impact event.

*Remote Sensing.* At optical, ultraviolet, and infrared wavelengths, spectrophotometric and color-differencing techniques have been used to investigate the spectral properties of solar system objects. Insofar as these methods provide resolutions approaching those of familiar imaging systems, they can produce data directly applicable to individual craters. Specifically, in the lunar case, spectral, albedo, and, in some instances, chemical characteristics of various crater units and deposits have been distinguished, and changes in color and reflectance brought about by impact events have been studied. In addition, the stratigraphy of the target can often be determined from such studies. Spacecraft carrying gamma- and x-ray detectors, magnetometers, and radio transmitters (used in gathering gravity data) have also garnered information valuable to crater studies.

*Laboratory Simulations.* Small-scale impact and explosion cratering experiments are characterized by stringent control of variables that would otherwise be weakly constrained or unknown during natural, large-scale events. For this reason, laboratory work presents



*Progression of morphology with crater diameter. On terrestrial planets small craters tend to be bowl-shaped (A). Larger craters (B) often display hummocky floors. At still larger diameters (C) terraced inner walls and central peaks are observed.*

the opportunity to determine the roles played by different factors in the cratering process, and, when scaling is correctly employed, direct extrapolation to larger structures can often be made. In addition, high-speed photography, stress and strain gauge measurements, and other techniques provide the luxury of recording the time histories of the phenomena associated with the mechanics of the cratering event. In a number of cases, the scale of these experimental events can be increased through the use of very large explosive charges.

*Computer Modeling.* The scaling relationships involved in extrapolating from small to large craters are only vaguely understood. This factor, combined with our inability to perform large-scale impact experiments, means that a substantial gap exists between our first-hand knowledge derived from cratering experiments and the information we need to interpret large-scale cratering events. Here we must resort to numerical modeling. Very large events under a variety of initial conditions can be simulated in a computer, and time-dependent phenomena can be followed in smaller time increments than is currently technically possible, even in the case of small events. Computer simulations also permit time to be "accelerated" if degradational or other long-time scale processes are to be investigated. Although such calculations are often expensive and sometimes depend on poorly characterized material properties, they

provide insights into processes that would otherwise be intractable, in terms of both time and physical magnitude.

### ***2.3.3. Craters in Geologic Studies: Some Established and Emerging Uses***

An impact is an event that occurs essentially independently of the physical properties of the target body. The results of the process, however, are influenced by the environment in which the event occurs. As pointed out earlier, a number of environmental factors play significant roles in determining the detailed outcome of a given impact.

Craters can be used in two principal ways to study the planet on which they occur. The traditional method applies statistical techniques to crater populations in order to learn about the age, history, physical properties, or other characteristics of a particular planet, region, or geologic unit. The second procedure, which has become more popular in recent years, uses individual craters or specific groups of craters as probes, markers, and windows in attacking specific problems often related to the stratigraphy of the region in which they occur.

*Statistical Studies.* One of the first applications of craters in planetary studies was the use of crater statistics to establish the relative ages of the lunar highlands and maria (Opik, 1960). Under the reasonable assumption of an areally isotropic impact flux, old surfaces will present greater areal densities of craters than will younger regions. Refinements of this technique have proved invaluable in interpreting the histories of planets and satellites explored during the past two decades (e.g., Soderblom et al., 1974; Neukum and Wise, 1976; Hartmann, 1977) (chapter 3). In addition, such information provides valuable constraints on the population of projectiles (e.g., Strom and Whitaker, 1976).

To first order, craters of a given size possess similar morphologies immediately after their formation. Any degradational modifications of the crater population (such as disappearance of morphological features due to blanketing, flooding, and other processes) can be treated statistically and used in studies of obliterational mechanisms. Coupled with crater-counting techniques, such degradational studies can aid in interpreting the geologic history of the region in question (e.g., Jones, 1974).

Growing knowledge of the physics and effects of impact cratering has encouraged further use of craters in more detailed and sophisticated investigations. For example, interplanetary comparisons of crater statistics, are suggesting the possibility that separate and distinct projectile populations were responsible for the bombardment of the solid-surface bodies during the early history of the solar system (Strom and Whitaker, 1976).

*Crater-Specific Studies.* The shock associated with an impact event fractures the target medium around and under the final cavity; consequently, large craters can serve as localized outlets for the extrusion of lava and as zones of weakness at which tectonic stresses can mobilize crustal material. For example, craters are believed to have served as eruption centers for a substantial fraction of the basalts of the lunar Mare Australe (Whitford-Stark, 1979); on Mercury, craters deformed by large apparent thrust features serve as convenient strain indicators for crustal shortening studies (Strom et al., 1975).

Since the shapes of craters can be predicted approximately (at least in rocky materials), these features have been used as valuable markers in gauging the thicknesses of various geologic units and deposits. Knowing the average interior geometry of a crater permits the depth of any infilling material to be estimated with a reasonable degree of accuracy (e.g., Whitford-Stark, 1979). By the same token, known distribution of rim heights as a function of crater diameter can be used to estimate the thickness of exterior deposits by documenting the degree to which craters of a given size are buried in a particular region (De Hon, 1974). For such purposes, accurate topographic data are necessary to establish the morphometric characteristics of the crater populations.

Classification of crater morphologies with respect to target type is producing information on the properties of the target materials as well as on the effects of these properties on the cratering process itself (e.g., Cintala et al., 1977; Wood et al., 1978). Since large quantities of heat are released in a very short time during an impact event, substantial volumes of the target are melted and vaporized. Under these conditions, parameters such as volatile content appear to play a significant role in influencing the cratering style and the final crater morphology. For example, few (if any) craters with central pits are observed on dry bodies such as the Moon and

Mercury, but their abundance increases from Mars to Ganymede and Callisto—bodies which are believed to have volatile-rich surfaces.

The availability of accurate topographic maps and a better understanding of possible mechanisms involved in the large-scale fracturing of crater floors has permitted the mathematical modeling of such endogenic processes (Hall et al., 1980). On a much larger scale, mathematical analysis of basin structure is leading toward better models of the lunar (Melosh, 1978; Solomon and Head, 1979) and martian interiors (Solomon et al., 1979). Such calculations, however, depend strongly on the values assumed for various material parameters, including the effective crustal and mantle viscosities, most of which are poorly known. Schaber et al. (1977) have attempted to constrain the effective viscosity of the mercurian mantle by analyzing those members of the planet's crater population which are believed to have adjusted isostatically. Thus, craters of all sizes can be useful tools in deciphering the histories of their parent planets.

#### ***2.3.4. Persistent Problems and Unanswered Questions***

Our knowledge of craters and cratering mechanics has grown remarkably over the last two decades. The first-order problems of origin and mode of formation have been treated in abundant detail, but a large set of more specific questions remains to be answered. Impact cratering has been a ubiquitous geologic process throughout the history of the solar system, and it is likely that crater- and basin-forming events affected significantly the formation of early planetary crusts, including that of Earth. Craters also provide an essential means of establishing planetary chronologies and clarifying the evolutionary histories of projectile populations. The processes that degrade, erode, and otherwise modify craters must be better understood if chronologies derived from crater counts are to be trusted.

Important specific questions that must be addressed include:

1. How do variables such as projectile characteristics (which include size, shape, composition, material properties, and impact velocity and angle), target properties (both physical and chemical), gravitational acceleration, and atmospheric pressure affect the geometry of the resulting crater, especially as the magnitude of the event increases? More specifically, how is energy partitioned during an impact event, and how

does this partitioning change as a function of the variables? A specific corollary to this question that is becoming increasingly important as the outer solar system is explored more thoroughly is, what are the specific differences between cratering in dry rock and in more volatile targets? Not only might crater geometry and impact energy partitioning be different, but significant departures from the more familiar silicate style of cratering might occur in ice-rich targets. The "central pits" cited earlier provide a good example. Why do they occur in a dominant fraction of the large craters on Ganymede and Callisto, in some craters on Mars, but in few, if any, craters on the Moon and Mercury? If volatiles in the target material were responsible for their formation, why are central pits also rare on Saturn's icy satellites?

2. What is the shape of the transient cavity of a large crater before its modification by target rebound, wall collapse, and other mechanisms? What are the relative contributions of ejection and compression in determining this geometry? At what point in time do the various modification mechanisms set in to produce the final crater shape? What are the dominant modification mechanisms? Knowledge of the transient cavity's geometry is of utmost importance in understanding the depth of excavation and volume of ejecta, the volumes of autochthonous breccia formed by the shock, the depth of origin of central peak material, the depth to the megaregolith-bedrock transition, and other crucial parameters. This problem is related to the first question, in that the geometry of the transient cavity will probably depend on many, if not all, of the variables mentioned above.
3. Which ring in a given multiring basin most closely corresponds to the rim of the cavity of excavation, and what are the origins of the remaining rings? Is the outer ring the result of very large-scale slumping, and, if so, did the fault surfaces serve as conduits for the eruption of lavas? Why do ring geometries seem to be virtually independent of target type, gravitational acceleration, and, presumably, projectile characteristics? Answers to such questions are essential, since large impact structures must have played a significant role in the early evolution of surfaces in the solar system.
4. Was only one population of projectiles responsible for the

craters observed throughout the solar system, or were several populations involved? What were the dynamical, physical, and chemical characteristics of these populations? How did the population change with time? These questions must be answered if the chronologies of planetary surfaces are to be determined through crater-counting techniques (chapter 3).

5. What changes occur in the petrologic, petrographic, chemical, and physical properties of the target rock during an impact event as a function of distance from the impact site? Can such metamorphic traits be uniquely interpreted in terms of a specific set of impact-induced conditions? Can the preimpact rock properties and stratigraphy be reconstructed from collected samples? Such questions are particularly relevant in the case of large craters and basins.

#### **2.3.5. Summary**

Although many first-order questions concerning the origin, formation, and morphology of craters have been answered satisfactorily as a result of data acquired through a variety of techniques during the past decade, some detailed aspects of the cratering process remain poorly understood. These more detailed questions, involving the sources, fluxes, and characteristics of projectiles, the specific physical mechanisms and sequences of events of both large and small time scales involved in the crater excavation process, as well as the effects of shock on planetary materials, must be pursued vigorously. Since so many aspects of planetary geology are dependent on the use of craters as essential tools, a vigorous program of crater research must be maintained to resolve the remaining unanswered questions.

#### **2.4. Eolian Processes**

Many physical and chemical processes modify planetary surfaces. Eolian is defined (Gary et al., 1972) as "pertaining to the wind; esp. said of rocks, soils, and deposits (such as loess, dune sand, and some volcanic tuffs) whose constituents were transported (blown) and laid down by atmospheric currents, or of landforms produced or eroded by the wind, or of sedimentary structures (such as ripple marks) made by the wind, or of geologic processes (such as erosion and deposition) accomplished by the wind."

Thus, any planet or satellite having a dynamic atmosphere and a solid surface is subject to eolian processes. A survey of the solar

Table 1.—*Surface Environments of Planets Subject to Eolian Processes*

|  | Venus           | Earth                           | Mars            |
|--|-----------------|---------------------------------|-----------------|
| Surface pressure (mb)  | $9 \times 10^4$ | $10^3$                          | 7.5             |
| Mean temperature (°C)  | 480             | 20                              | -20             |
| Composition of atmosphere                                      | CO <sub>2</sub> | N <sub>2</sub> , O <sub>2</sub> | CO <sub>2</sub> |
| Surface gravity ( $g_{\oplus} = 1$ )                           | 0.88            | 1                               | 0.38            |
| Minimum threshold friction speed (cm/sec)                      | 2               | 15                              | 160             |
| Particle diameter most easily moved by winds ( $\mu\text{m}$ ) | 60              | 80                              | 100             |

system shows that at least Earth, Mars, Venus, and possibly Titan meet these criteria (Table 1). In this section we review our knowledge of eolian features and activity, consider the relevance to planetary geology of understanding eolian processes, and discuss the means for studying these processes in the planetary context.

#### 2.4.1. *Review of Eolian Activity on the Planets*

Wind blowing across a planetary surface has the potential for directly eroding material and redistributing it to other areas. Most eolian erosion occurs through abrasion caused by windblown particles of sand size or smaller. Winds transport sediments via three modes: suspension (mostly silt and clay particles, i.e., smaller than about 60  $\mu\text{m}$ ), saltation (mostly sand-size particles, 60 to 2000  $\mu\text{m}$  in diameter), and surface creep (particles generally sand size and larger). The ability of wind to move particles is a function of atmospheric density and velocity (low densities require stronger winds than high densities), particle size, shape, and density, and other less important factors. Wind threshold curves define the minimum wind speeds required to initiate movement of different particles for given planetary environments (Bagnold, 1941).

*Earth.* On Earth, eolian processes occur principally in arid regions, near shorelines, and wherever strong slope or thermal winds occur (e.g., near glaciers). Because vegetation tends to retard near-surface winds and trap windblown sediments, eolian processes are enhanced and in some cases become dominant in vegetation-free regions, which constitute a large percentage of Earth's solid surface. Eolian deposits occur throughout the geologic column and include



ancient sand seas and loess deposits. Given that sands can be important reservoirs for petroleum, knowledge of form and structure of eolian deposits is of practical importance.

Because the extent of desert areas changes with time and climate, there is great economic and social interest in understanding the factors (including eolian processes) that are involved in causing such changes. The term "desertification" is used to describe the process by which areas are converted to deserts. In the past decade much research has focused on desertification, in part coordinated by UNESCO.\* Fundamental to this research is an understanding of the mechanics of eolian processes—knowledge that is required also for extrapolations to other planetary environments.

*Mars.* Windstorms were believed to occur on Mars even before the successful space probes in the early 1970s returned conclusive evidence of eolian activity. Earth-based observations beginning in the nineteenth century showed seasonal albedo patterns that were attributed to a variety of causes, including schemes which involved dust storms and other eolian processes (Briggs et al., 1979).

As our knowledge of the composition and density of the martian atmosphere improved, theoretical predictions of the wind velocities required to set particles in motion were made. Because of the low atmospheric density on Mars, the estimated minimum wind speeds were about an order of magnitude higher than those on Earth (Sagan and Pollack, 1969). Wind tunnel tests conducted under low atmospheric pressure to simulate martian conditions substantiated these early estimates (Greeley et al., 1976, 1980a).

With the arrival of Mariner 9 and the Soviet spacecraft Mars 2 and 3 at Mars in 1971 during a major global dust storm, the speculations concerning the efficacy of martian eolian processes were amply confirmed. After the dust cleared, the Mariner 9 cameras revealed abundant features attributed to eolian activity, including sand dunes, yardangs (wind-sculpted hills), various pits and grooves, and albedo patterns on the surface (termed variable features) that changed in size, shape, and position with time. After the Mariner 9 mission it was suggested by some (e.g., Sagan, 1973) that the rate of eolian erosion on Mars is very high, based on three factors: (1) the high wind speeds required for particle motion on

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\*United Nations Educational, Scientific, and Cultural Organization.

the planet, (2) the high frequency of dust storms documented by telescopic observations from Earth, and (3) the variety and large number of surface features attributed to wind erosion and deposition. It was reasoned that sand grains, once set into motion by the wind, would be accelerated to high speed and would be very effective in "sandblasting" the surface.

The Viking mission has added substantially to the inventory of martian eolian features, including the discovery of the vast north polar sand sea, equal in size to the Sahara sand sea on Earth. Examination of the highest-resolution Viking Orbiter images (better than about 15 m per line pair) shows that sand dunes occur in most parts of the planet (Thomas, 1982). Viking Landers showed, for the first time, the windswept surface of Mars, including views of eolian deposits and rocks that appear to be wind eroded. The Viking mission also caused a reassessment of wind erosion rates on Mars. Although Viking verified the widespread occurrence of eolian features, several lines of evidence now suggest that the rates of eolian processes may not be as high as previously thought. For example, more than four years of monitoring wind speeds at the two Viking landing sites show that the near-surface winds seldom attain threshold speeds. More importantly, the Viking Orbiters reveal numerous surfaces that have small ( $\sim 10$  m), fresh-appearing impact craters; their presence signals surfaces at least hundreds of millions of years old that have been modified very little by erosion of any type. Thus, there appears to be a conflict between the predicted high rate of eolian erosion on Mars and the constraints posed by the Viking results. Resolving this conflict is important for understanding Mars as a planet, since the answer is related closely to many important questions, such as:

1. Do the sand dunes and other long-lived eolian features represent the current eolian regime, or are they relict features formed at a time when the climate on Mars was more favorable for eolian activity (e.g., higher atmospheric density)? This question has a direct bearing on understanding the climatic history of Mars.
2. What is the lifetime of topographic features on Mars, especially impact craters? Relative dating of surfaces on Mars is based primarily on numbers of superposed impact craters. Is eolian erosion or burial by eolian deposits significant? If so, what sizes of craters are affected and in what manner?



*A sea of sand dunes on Mars.*

3. What is the role of eolian processes in modifying the surface? Is eolian erosion rapid enough to keep “fresh” bedrock exposed? These questions are intimately linked to knowledge of rates of eolian erosion, and have a direct bearing on attempts to characterize the composition of the martian surface via remote sensing.

*Venus.* The dense atmosphere of Venus appears capable of sustaining eolian processes. Venera landers measured wind speeds of about  $2 \text{ m s}^{-1}$  at two locations, and extrapolations of measurements obtained by the Pioneer Venus probe at a third location yield values

of about  $1 \text{ m s}^{-1}$ . Theoretical studies and extrapolations of wind tunnel experiments to the venusian environment suggest that these values are well within the range required to initiate particle movement on the surface (Greeley et al., 1980b).

Venera images of the surface of Venus show a bimodal distribution of particle sizes—coarse fragments of cobble size (several centimeters and bigger) and fine-grained material. It has been suggested that the fine-grained material has been transported by wind and that the coarse fragments have been shaped by wind erosion.

Although the requirements for eolian activity on Venus appear to be met—winds capable of moving grains and a supply of particles in the appropriate size range—the degree to which eolian processes modify the surface at present and how effective they have been in the past remain to be studied.

*Titan.* Voyager measurements have shown that this icy satellite has a thick nitrogen-rich atmosphere. The surface temperature and pressure are 90 K and 1.6 bars, respectively. Whether the atmosphere is dynamic and whether granular particles exist on the probably icy surface are unanswered questions.

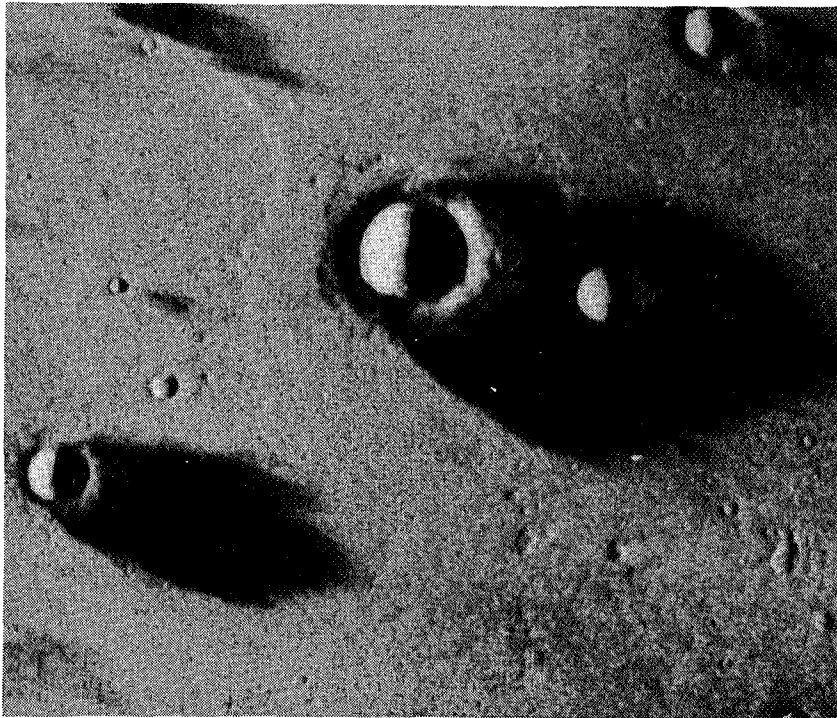
Thus, Earth, Mars, probably Venus, and possibly Titan are all subject to the same basic eolian processes (erosion, transportation, and deposition of windblown material), but the surface environments are strikingly different. These differences afford the opportunity to investigate a basic geologic process in a comparative sense. Because terrestrial processes and features have been studied for many years, Earth remains the primary data base. However, because surface processes are much more complicated on Earth—primarily because of the presence of liquid water and vegetation—many aspects of eolian processes that are difficult to assess on Earth are more easily studied on other planets. For example, on Earth cohesion among particles resulting from moisture is difficult to separate from that resulting from electrostatic charges; in the comparatively dry atmosphere of Mars, effects of water are less important, and the general problem is made simpler.

#### ***2.4.2. Relevance of Eolian Studies to Planetary Geology***

Eolian processes can redistribute enormous quantities of sediment over a planet's surface and form features large enough to be seen from orbit. On Earth deposits of windblown sediments can be hundreds of meters thick. Any processes capable of effecting such

changes must be relevant to understanding the present and past geologic environment of a planet. Furthermore, because eolian processes involve the interaction of the atmosphere and lithosphere, an understanding of eolian activity sheds light on meteorologic questions. In this context, eolian activity can be examined in terms of large-scale modification, small-scale modification, and observable active processes, such as dust storms and changing surface features.

Large-scale modification of a surface can be defined as involving features on scales that can be observed from orbiting spacecraft. Such features can be either erosional or depositional. By far the most useful eolian feature for interpreting eolian processes is the dune, a depositional landform. A recent document edited by McKee (1979) describes the major sand deposits on Earth and discusses various dune forms; because much of the book is based on spacecraft images, it is particularly relevant to planetology. Both the planimetric shape and cross-sectional profile of dunes can reflect the prevailing winds in a given area. Thus, if certain dune shapes



*Dark wind-eroded streaks associated with craters on Mars.*

and/or slopes can be determined from orbital data, local wind patterns can be inferred. Repetitive viewing of the same dunes as a function of season may reveal seasonal wind patterns. Although dunes seldom change significantly in plan form with season, the slip face on the dune crest can be observed to show the influence of alternating wind directions.

Identification of dunes demonstrates the presence of sand-size (60 to 2000  $\mu\text{m}$ ) particles because sands are the only materials known to accumulate in dune deposits on Earth (Bagnold, 1941), and there is nothing in the physics of windblown sediments to suggest that the situation would be different on Mars, Venus, or Titan.

On Earth great quantities of silt and clay are transported in dust storms. This material is eventually deposited as vast sheets or mantling units, and is commonly termed loess. Loess deposits exceeding hundreds of meters in thickness are found throughout the geologic column. Even when relatively young and well exposed, loess deposits are nearly impossible to identify by remote sensing. Yet identification of such deposits could be very important in understanding planetary surfaces. For example, substantial areas of Mars are interpreted to be mantled with ancient eolian sediments. However, other processes could also lead to terrains of similar appearance. Thus, some definitive means of identifying fine-grained eolian sediments by remote sensing is needed.

Large-scale eolian erosional features include (1) pits and hollows (called blowouts) that form by deflation or removal of loose particles, (2) wind-sculptured hills called yardangs, (3) wind-eroded "notches" in ridges, and (4) general, unclassified wind-eroded landforms. Some of these features can be diagnostic of bedrock materials. For example, although yardangs have been reported in crystalline rocks, they form most commonly in friable, nonindurated clastic deposits such as loess.

Impact crater frequency distributions are widely used in planetary geology to obtain relative dates for different surfaces (chapter 3). On planets having active eolian processes, the erasure of craters by erosion or burial by eolian sediments can drastically alter the crater record and invalidate crater-derived ages. Thus, a knowledge of rates of eolian erosion and deposition for a wide range of planetary environments is required in order to assess the possible effects on the impact crater record.

Small-scale eolian features include ventifacts (wind-shaped rocks)—features that can be observed only directly on the ground. Ventifacts can provide information about local wind directions and the length of time a surface has been exposed. Identification of ventifacts has relevance to other aspects of planetology. For example, rocks at the Viking landing sites that show pitted surfaces have been interpreted as vesicular igneous rocks and form part of the basis for identifying the surrounding plains as volcanic; alternatively, the pitting could be the result of eolian erosion.

Eolian processes can both mix and sort sediments. Deposits consisting of a wide range of particle sizes, such as river sediments or glacial deposits, when subjected to winds may have the coarser particles left behind, leading to “desert pavement” surfaces. Conversely, windblown dust derived from a wide range of rocks may become compositionally “homogenized” in dust storms and settle over extensive areas. In either of these cases (wind-sorted or wind-mixed deposits), remote sensing data could lead to erroneous conclusions about the composition of the areas observed. Knowledge of how eolian processes operate under a wide range of planetary environments and recognition of identifying characteristics are critical to the problem.

Observations of certain eolian features can provide direct information about the atmosphere. For example, crater streaks on Mars are albedo patterns on the surface that show surface wind direction; they occur in great numbers over much of the planet’s surface. Repetitive imaging of these and other variable feature patterns has shown that many of them disappear, reappear, or change their size, shape, or position with time. Mapping the orientations of variable features has been used to provide information on the near-surface atmospheric circulation of the martian atmosphere at different seasons (Veverka et al., 1977; Thomas et al., 1979).

Investigation of past eolian regimes on Mars is an important aspect of studying the surface history of the planet. Although the orientations of most eolian landforms have been related to the current atmospheric circulation patterns, the degree of erosion and deposition suggested by the morphology and size of many of these features cannot be explained completely by the contemporary eolian regime. Arguments for major variations in atmospheric conditions due to changes in the obliquity and orbit of Mars suggest that the wind efficiency has fluctuated widely throughout the planet’s histo-



*Evidence of eolian processes on Mars: an extensive area of wind-sculpted linear hills (yardangs), with sand dunes at lower right.*

ry. Large-scale ancient deposition and possible active deflation are evidenced by features such as the partially exhumed craters and the massive, layered polar deposits. The nonuniformity of wind direction inferred from yardangs, an erosional landform, within a single



region is further evidence of these fluctuations. Since the stratigraphic history of the planet is closely related to the large-scale variations of past eolian regimes, these must be determined as precisely as the preserved record permits.

#### ***2.4.3. Suggested Approach for Investigating Eolian Processes***

Since eolian processes incorporate elements of geology, meteorology, physics, and chemistry, a unified study requires knowledge in all these areas or a multidisciplinary approach. The approach commonly used is to isolate parts of the eolian process for detailed study, as was done in the pioneering work of Bagnold (1941), who analyzed the physics of windblown sand. Once the fundamental principles are understood, it is possible to extrapolate to a wide range of conditions, i.e., other planetary environments. Before this can be done, however, it is necessary to fit the results from the studies of isolated parts of the problem back into the system. For example, Bagnold's work on threshold winds for particle movement was carried out principally in wind tunnel studies; before making generalizations, he field tested the results using natural sands. In the study of planetary eolian processes, we seldom have the opportunity to field test our extraterrestrial ideas. Thus, we must rely on a somewhat different method, which can be outlined as follows:

1. Identify general problem and isolate specific factors for study (e.g., wind threshold speeds for particles of different sizes on Mars).
2. Investigate the problem under laboratory conditions where various parameters can be controlled for the "Earth case" (e.g., wind tunnel tests of threshold speeds).
3. Field test the laboratory results under natural conditions to verify that the simulations were done correctly (e.g., threshold tests in the field).
4. Correct, modify, and/or calibrate the laboratory simulations to take account of the field results.
5. Carry out laboratory experiments for the extraterrestrial case, duplicating or simulating as nearly as possible the planetary environment involved (e.g., threshold tests under martian conditions).
6. Extrapolate the results to the planetary case, using the labo-

ratory results and theory (for parameters that cannot be duplicated).

7. Field test the extrapolation via spacecraft observations and apply the results to the solution of problems involving eolian processes.

The benefits of this approach are not only that it provides a logical means for understanding extraterrestrial problems, but that it contributes toward solving eolian problems on Earth as well.

#### **2.4.4. Summary**

Some of the key questions that should be addressed through ongoing and future research in planetary eolian phenomena include:

*How are dust storms initiated?* This question applies to both Earth and Mars. Dust storms involve very fine-grained materials (typically a few micrometers in size). The "threshold curve" shows that extremely strong winds are required to move such fine material, making it unlikely that such grains are placed into suspension by direct entrainment. The explanation frequently given is that sand-sized grains (relatively easily moved) placed into saltation impact dust particles, dislodging them from the surface and subjecting them to entrainment by the wind. This scenario does not explain frequent dust storms on Earth that begin in areas lacking sand. Other factors may be involved, perhaps related to electrostatic effects, clumping of fine particles into sand-sized aggregates, or other triggering mechanisms. This is a general problem that has received too little attention despite its importance to eolian studies on both Earth and Mars.

*What are rates of eolian erosion in various planetary environments?* Despite much interest in eolian erosion (both deflation and abrasion), relatively few studies have been done even on Earth that provide quantitative data, much less that are relevant to other planets. There are two parts to the problem: one deals with erosion on a small scale (e.g., individual rocks), and the other concerns erosion of landforms (e.g., crater rims).

*What is the evolution of eolian landforms?* Many studies have been carried out that define stages of development for various eolian features on Earth. In some cases there is disagreement over both the results and the interpretations. For example, some investigators

consider certain types of longitudinal dunes to have evolved from other dune forms and to represent a mature stage of eolian activity; the apparent absence of longitudinal dunes in the north polar region of Mars would therefore signal a relatively recent development of dune-forming processes. However, before such an interpretation can be made, two important questions must be answered: first, is the basic idea valid, and second, does it apply to Mars? This and other models of the evolution of eolian landforms should be tested on Earth, and studies should be done to determine how to apply them to extraterrestrial environments.

*What are the compositions of eolian sediments on various planets?* On Earth, most eolian sediments are quartz sand and silts, various clay minerals, plus minor amounts of particles of other compositions (gypsum sands, calcite sands, etc.), and most of the knowledge of the physics of particle motion and eolian features such as dunes deals with these materials. If windblown particles exist on Titan, they may be composed of methane ice or other frozen volatiles. The composition of eolian particles on Venus is completely open to speculation; on Mars, quartz is probably absent or is only a minor constituent because major source rocks for quartz, such as granites, are apparently absent. Given the widespread occurrence of basaltic lava flows, the low albedo of martian dunes, and the prevalence of mafic to ultramafic compositions suggested from spectral studies, it is believed that basaltic sands are common on Mars. How do windblown basaltic sands behave? What is their evolution? How efficient are they as agents of abrasion in the eolian environment? Do they accumulate in deposits having morphologies different from those made of quartz particles? At what rate do they weather into clay-like material under martian conditions? These and other questions are intimately linked with understanding the general sedimentary cycle on Mars. Similar sets of questions can be asked about Venus and possibly Titan.

*What are the eolian conditions on Venus?* The physics of windflow and particle movement in the high-temperature and high-pressure atmosphere of Venus involves flow regimes not previously investigated. Even such fundamental questions as threshold wind speeds can only be estimated crudely at present.

*How has the eolian environment on Mars changed through time?* There is ample evidence that changes in Mars' climate have occurred in the past (Carr, 1981; Baker, 1982) and that these changes have

been accompanied by variations in the eolian cycle (e.g., changes in the number and severity of global duststorms [Pollack and Toon, 1982]). Although the program outlined above does not directly address such questions, it should lead to a better understanding of the physics of eolian processes, which in turn should make it possible to begin addressing these more complicated problems during the coming decade.

## **2.5. Fluvial Processes**

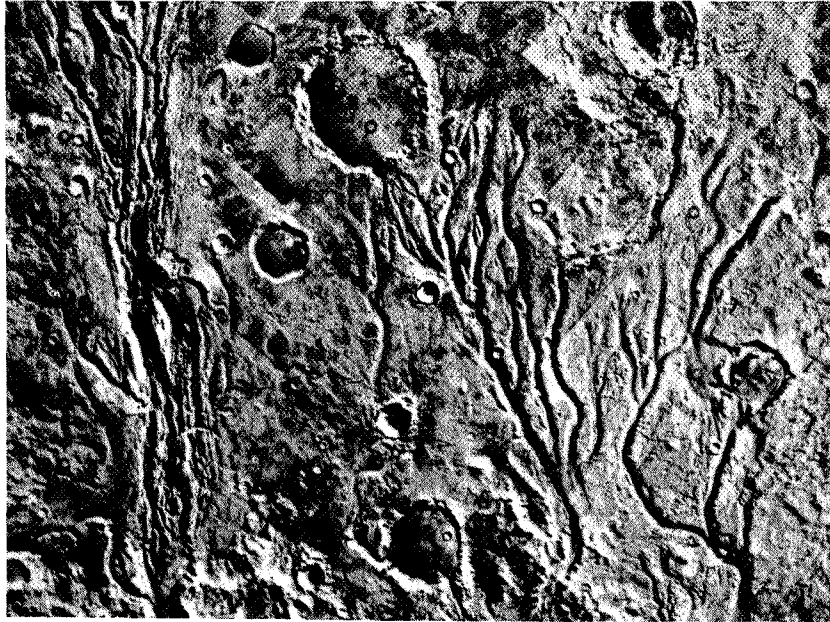
On Earth, worldwide surface reservoirs, recirculating ground water, and atmospheric cycles form the so-called hydrologic system. This system, which drives most surface geologic processes and sustains the operations of the biosphere, has operated as long as we can trace geologic history. In 1972 Mariner 9 revealed the widespread existence of "large channels" on Mars, which were generally interpreted as evidence for the presence of significant quantities of liquid water on the planet's surface at some time past. Today Mars has a hydrologic cycle, but one greatly reduced in intensity and vigor from that inferred to have existed in the distant past. There are reservoirs of frozen water in the polar caps and possibly extensive areas of ground ice. The polar caps could be part of a global hydrologic system consisting of a poleward atmospheric flow of water vapor and an equatorward return migration of ground water.

Although water is certainly the most abundant, and perhaps the only, liquid responsible for fluvial processes in the solar system, more exotic possibilities cannot be ruled out. For example, Voyager results suggest that fluvial processes involving liquid hydrocarbons could occur on the surface of Titan. Yet it must be admitted that any discussion of fluvial processes at the present time must concentrate on Earth and Mars as locales, and on liquid water as the agent.

### ***2.5.1. Water as a Geologic Agent***

Water is a dominant geologic agent on Earth, operating on scales from the global to the molecular. A true appreciation of the evolution of a planet such as Mars requires that we investigate the role of water in its geologic system as well. The primary questions to be answered are:

1. What constitutes diagnostic evidence of the (past) existence of water as a geologic agent?



*Large channels on Mars.*

2. How can one differentiate the geologic imprints of water in vapor, fluid, or solid form?
3. What are (were) the quantities of water involved?
4. What has been the temporal evolution of the types and intensity of the planet's water-related processes? Can we determine the evolution of the planet's water budget?

This section outlines how such questions might be answered by summarizing what has been learned and what potentially might be learned in four closely connected areas: (1) conceptual studies of sediment dynamics, (2) theoretical and laboratory modeling of fluid flow and sediment transport, (3) mapping of surface geology on Mars, and (4) field studies of analogs on Earth.

#### ***2.5.2. Dynamics of Fluvial Sedimentation***

Water acts to dislodge sedimentary particles through current shear, local channel bed pressure differentials (Bernoulli lift force), and inertial impacts (raindrops or grains saltating in the fluid). Once initiated, the patterns and intensity of sediment transport are controlled by many factors, including fluid shear stress, turbulence,

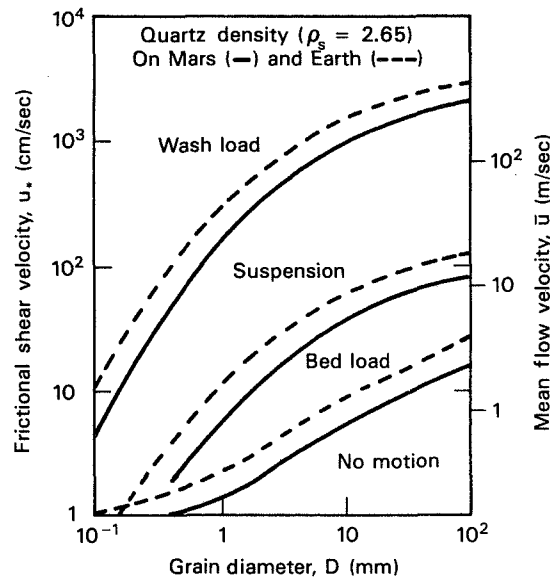
viscosity of the water/sediment mixture, size distribution of the particles, and the rate of sediment supply to the transport systems. The interaction of all these variables in terrestrial sediment transport systems is fairly well understood. However, this knowledge has been acquired largely through observation and experiment rather than through basic theoretical physical analysis. Given this semiempirical basis, we are poorly equipped to transfer the information to other planets, on which the physical parameters may differ from those on Earth. On the other hand, asking questions about sediment dynamics on other planetary bodies forces us to penetrate deeper into the physics of the problem.

Current investigations of general fluvial sediment dynamics on other planetary surfaces (specifically Mars) include studies of (a) the relative role of wash load versus bed material load, (b) the effect of gravity acting on fluids in different environments, (c) the rate of evaporation from the fluid surface, (d) the efficiency of particle entrainment, and (e) the capacity for bedrock erosion by cavitation and macroturbulence.

Sediment transport in a fluvial system is usually separated into bed material load and wash load based on the settling velocities of the particles. Bed material load is that fraction of the total load which is locally derived from the bed. Wash load, on the contrary, is that sediment population which is moved through the river system entirely in suspension.

The distinction is essential because the relative magnitudes of the two populations are controlled by entirely different factors (Shen, 1971). The bed load is governed by the transport capacity of the river. Transport rates can be calculated once the river hydraulics are known. For wash load, on the other hand, the actual amount being transported is governed by rates of supply or production of the drainage basin. The wash load cannot be calculated from river hydraulics. Wash load transport requires little or no expenditures of stream power; therefore, very fine particles may be carried in nearly unlimited quantities.

Because the sediment transport mode is largely a function of the ratio between particle settling velocity and the shear stress acting on the bed, both of which depend on the acceleration of gravity, rivers on Mars will have transport characteristics different from those on Earth. Komar (1980) suggests that the floods inferred to have carved the large equatorial channels on Mars could



*Modes of transport for quartz-density grains on Mars and Earth. Due to lower surface gravity on Mars, smaller velocities are needed to move grains of a given size.*

have transported cobbles in suspension and carried all sand-sized material as wash load. The figure above compares the modes of transport of quartz-density grains on Mars and Earth.

In another investigation of the effects of reduced surface gravity, Komar (1979) compared submarine channels on Earth to the large outflow channels on Mars. Due to buoyancy, the effective acceleration of gravity ( $g$ ) acting on a deep-sea turbidity current is reduced to about  $1.4 \text{ ms}^{-2}$ , from the normal subaerial value of  $9.8 \text{ ms}^{-2}$ . On the surface of Mars ( $g = 3.7 \text{ ms}^{-2}$ ) water flow would take place in a gravity field intermediate between that obtaining for river flows on Earth and that governing deep-sea turbidity currents. Therefore, deep-sea channels provide important terrestrial analog systems to test the effects of gravity on channel formation.

One unknown parameter in all hydraulics calculations for Mars is the atmospheric environment at the time of active channel flow. If atmospheric conditions were anything like those at present, one would expect rapid evaporation and perhaps the formation of a layer of surface ice or ice fragments. Calculations by Wallace and Sagan (1977) suggest rapid formation of a meter-thick ice layer,

with possible continued flow of liquid water underneath for many hundreds of kilometers. This work suggests that the observed channels could have been formed under climatic conditions not very different from those present today.

Nummedal (1977) studied the case of particle entrainment into flow over a noncohesive bed of sediments. Using the Shields entrainment function and scaling for martian gravity, he found that initiation of movement on Mars for particles ranging in size from 1 cm to 10 m will occur for shear stresses only 25 percent of those required on Earth. In the case of entrainment from a cohesive or lithified channel bed, both fluid and bed characteristics determine the efficiency.

Baker (1978) has argued that the martian surface may provide conditions particularly favorable for bedrock erosion by combined action of cavitation and macroturbulence. There is, however, a question about the effectiveness of cavitation as an erosional process on Mars if channel flow occurred under the present low atmospheric pressure.

In spite of such investigations, it is not possible at present to calculate the erosion rates, predict the characteristic channel bed-forms or even the viscosity of the fluid that actually carved the channels. The theoretical work on fluvial sediment dynamics must be continued, and experimental investigations under conditions similar to those existing on Mars aimed at testing directly various theoretical predictions should be initiated.

### ***2.5.3. Channel and Valley Morphology on Mars***

Studies of basic sediment dynamics have revealed that, due to differences in the acceleration of gravity and ambient pressure, sediment entrainment and transport processes on Mars should differ significantly from those on Earth. Yet we are a long way from theoretically predicting the ultimate channel form based on hydraulics and sediment loads. Consequently, the approach taken to explain the origin of channels on Mars is to investigate terrestrial analogs, correctly appraise their mode(s) of origin, and then test, in light of differences in flow dynamics on Mars, the applicability of the terrestrial models.

In this discussion a distinction is made between channels and valleys. Channels refer to large sinuous or curvilinear depressions that contain direct evidence of fluid flow, such as linear grooves,

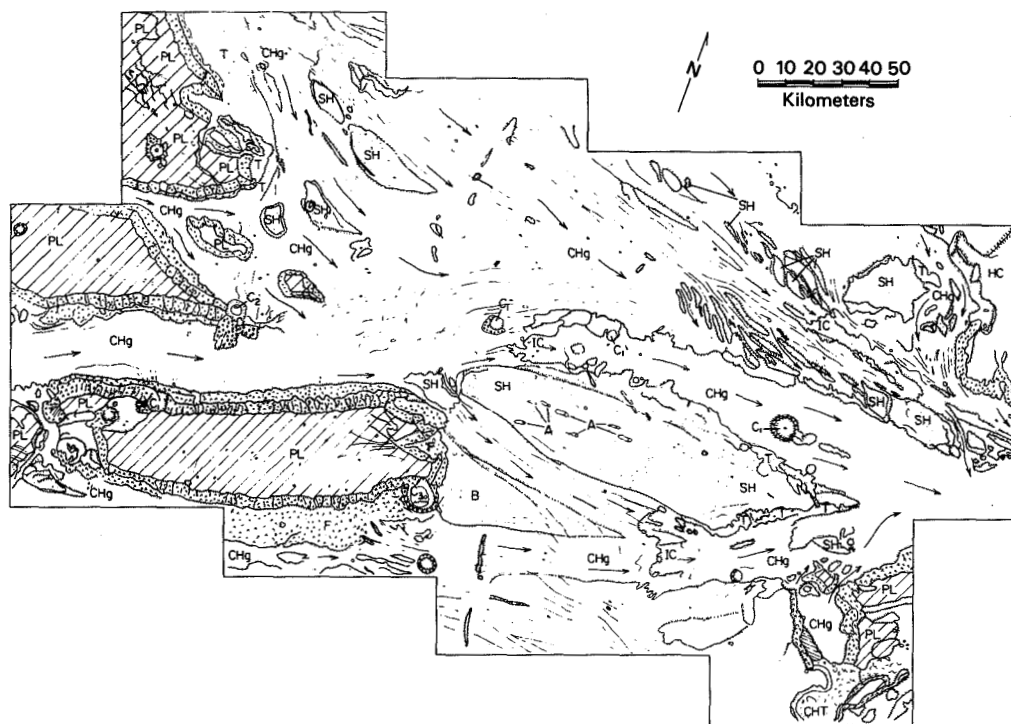


streamlined islands, and other bedforms on their floors. Channels may or may not have tributaries; they may originate at a point or in a diffuse source area. Valleys refer to networks of generally smaller linear depressions. Although no bedforms are visible, valleys carry indirect evidence of being caused by fluid erosion, including integrated network patterns and tributary junction angles consistent with flow down the regional slope.

In the decade since their initial discovery, the channels on Mars have been variously attributed to nearly every conceivable fluid: water, ice, clathrate, wind, lava, and mud. The proliferation of models is in part due to the search for pure morphologic analogs, with little attention being given to dynamic similitude, and in part due to construction of theoretical models unconstrained by terrestrial experience. The current consensus is that wind and lava must be ruled out as a primary agent for the formation of channels on Mars. Therefore, the study of the origin of channels and valleys on Mars becomes synonymous with fluvial studies, taken in its broadest sense to include investigations of ground water and debris flows as well as river systems (Baker, 1982).

The two primary constraints on models for the channels on Mars come from (1) extensive geomorphologic mapping (Baker, 1978, 1982), which has demonstrated that large floods were responsible for the primary formation of many channels, and (2) theoretical studies that indicate that surface flow on Mars might have exhibited a dynamic similarity to terrestrial flows in submarine settings (Komar, 1980).

Subaerial terrestrial analogs are presently studied much more extensively than submarine ones within the Planetary Geology program, although Nummedal and Prior (1981) have argued that the terrestrial submarine environment—specifically the Mississippi Delta front—provides valuable analogs for a wide range of instability features associated with some of the large channels on Mars. Investigations of catastrophic flood features, moderate-discharge braided stream features, mudflows, and investigations of the origin of deeply incised bedrock canyons have all provided analogs to selected channels or valleys on Mars (Baker, 1982). Literature reviews of the morphologic imprints of large pleistocene glaciers in arctic Canada suggest that glacial action could also produce many of the fine-scale features observed within the large martian outflow channels (Lucchitta et al., 1981). Field investigations of these features



*Geomorphologic map of Kasei Vallis, one of the largest martian channels.*

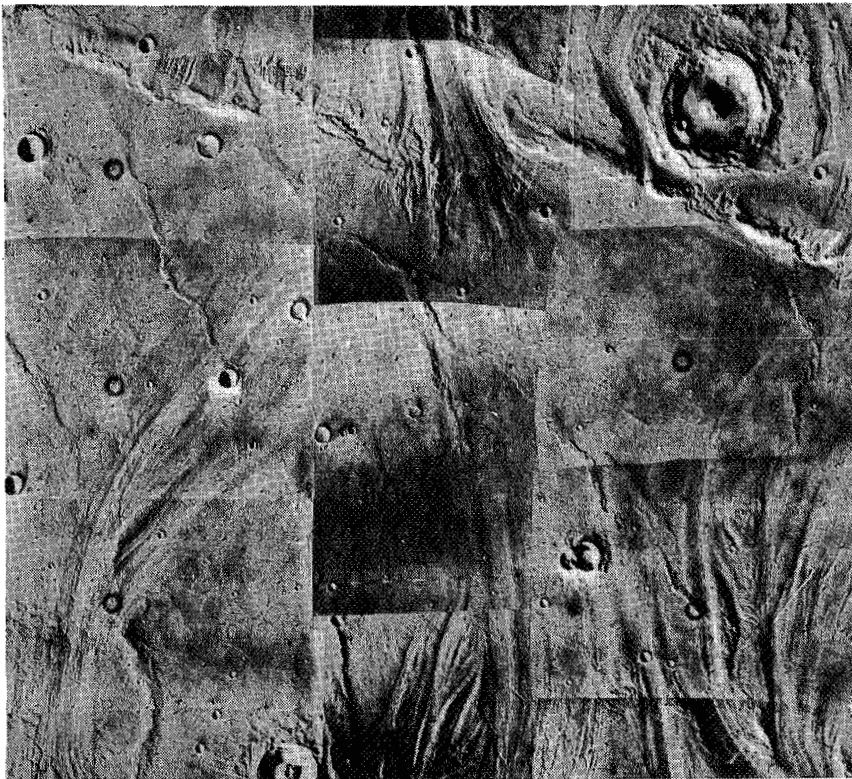
from the viewpoint of martian analogs are desirable, as is continued work on submarine analogs to martian outflow channels (Nummedal and Prior, 1981).

Among ideas on the origin of the large channels on Mars, the catastrophic flood hypothesis has gained the most widespread acceptance (Masursky, 1973; Baker and Milton, 1974). The channeled scabland of the Columbia Plateau in Washington is generally considered to be the best terrestrial analog (Baker and Nummedal, 1978). The scale of the scabland channels, the anastomosing system, the dry falls and cataracts, the linear channel floor grooves and streamlined hills all have their inferred equivalents on Mars.

Three theories have been put forth to explain possible catastrophic release of water on Mars. Soderblom and Wenner (1978) proposed that headward retreat of a scarp or small channel tributary intercepts a subsurface fluid reservoir, causing sudden dramatic increase in the flow rate and overburden collapse. Carr (1979)



*The channeled scablands of the Columbia Plateau in the State of Washington (above) are believed to have been fashioned by sudden catastrophic floods. A similar process may have formed many of the large channels on Mars (below).*



presented a detailed analysis of a model relating ground collapse and fluid release to the venting of a subsurface overpressure aquifer, and Nummedal (1978) suggested that liquefaction of a metastable subsurface sedimentary unit might be the origin of some of the chaotic terrain. According to this last hypothesis, the mud released would have been the primary channel-forming agent.

Studies of catastrophic flood features in Alaska (Thompson, 1980) and Iceland (Malin, 1980) have generally strengthened the flood hypothesis for the origin of Mars channels. Yet, as demonstrated by Boothroyd (1980) in a comprehensive study of quaternary landscape development on the arctic slope of Alaska, many smaller-discharge braided streams that frequently change their active channels of flow may produce erosional features strikingly similar to the flood-generated streamlined shapes encountered in the channeled scabland. This fact demonstrates that no single geomorphic feature or channel bedform in isolation is diagnostic of a process or origin. Rather, the entire assemblage of related features must be correctly interpreted in modeling the evolution of a landscape.

Perhaps the most important questions regarding the martian valley networks are their mode of origin and what this origin implies for the history of the martian climate. The ramified pattern of these valley systems has provoked comparisons with terrestrial drainage networks, particularly with those formed primarily by runoff associated with rainfall. This analogy has fueled the controversy of whether or not it has ever rained on Mars. Despite the evocative nature of hypotheses for martian rainfall, close scrutiny of valley interiors and network planimetric morphologies reveals features that are strikingly different from those associated with terrestrial rainfall-runoff drainage networks. A closer affinity in morphology appears to exist between the martian valleys and those formed in the terrestrial environment by basal sapping or seepage-fed runoff (Pieri, 1980; Baker, 1982).

Martian valley networks are distinctive in the notable absence of the dendritic pattern so common to terrestrial streams (Pieri, 1980). This pattern is characterized by a nearly uniform distribution of tributary directions and filling of the available intranetwork space. Many martian valley systems show pronounced parallelism and lack of tributaries in undissected intervalley terrain, thus appearing to be sparse relative to most terrestrial systems. Differences

of pattern with scale, along with system parallelism, most probably result from the introduction of fluid into the system from a restricted headward source region.

The presence of steep-walled, theater-like valley terminations suggests that headward extension by undermining and wall collapse ("sapping") may be an important process in valley formation on Mars (Pieri, 1980; Baker, 1982). Field studies in the Colorado Plateau and Hawaii have identified morphologic characteristics useful in differentiating valley systems cut by sapping from those produced by surface runoff. Sapping mechanics and wall retreat have been examined as functions of bedrock lithology, surface versus subsurface flow rates, and rock structure (Laity, 1980). Future work should emphasize detailed mapping and interpretation of martian networks and experimental and theoretical studies. The distribution, complex history, and origin of the valleys on Mars should provide a prime focus for continued fluvial studies.

Attempts to define the temporal evolution of the fluvial systems on Mars utilize both the standard terrestrial stratigraphic principles of superposition and a technique unique to extraterrestrial planets: relative age dating based on the frequency of impact craters. Carr (1980) and Masursky et al. (1980) summarize the current knowledge concerning the temporal evolution of the fluvial systems. According to Carr (1980), nearly all Mars valleys are found in the old densely cratered terrain. The valley morphology ranges from barely visible depressions to linear and curving troughs that are quite crisp in appearance. Their exclusive occurrence within densely cratered terrain suggests that they are all quite old. Crater counts on the small valleys themselves cannot be performed with accuracy, but the youngest, extensively dissected intercrater plains have around 3300 craters ( $>1$  km) per  $10^6$  km<sup>2</sup>, suggesting an absolute age of around 3.5 billion years. Plains formed since that time have few valleys or none at all. Conditions on Mars during all but its very early history appear to have been unfavorable for the formation of valley networks.

Channels, on the other hand, dissect the old cratered terrain as well as many younger units. Channel floors are in many cases large enough to permit crater counting. The crater dating suggests that large martian channels range in age through most of geologic history. Some highly degraded channels might be correlative with the

episode of valley formation. Others, for example, the big channels around Chryse Planitia, may date back to mid-martian history. Ares, Vedra, and Tiu Valles could be among the most recent geologic features on Mars.

Stratigraphic studies internal to each channel system are also important because they can reveal whether a channel was formed by one or multiple events. Few such detailed studies have been made so far, yet the basic information is available in the extensive Viking Orbiter data base.

#### **2.5.4. Summary**

Although the possibility of exotic fluvial processes (e.g., on Titan) must be kept in mind, to date evidence of fluvial processes has only been found on Earth and Mars. For Mars, fluvial studies have provided important clues to the planet's evolution and to its budget of volatiles. While many questions remain, a few answers are emerging. Large quantities of liquid water did exist at the time of primary channel formation. Yet, since there are no visible shorelines, significant amounts of liquid water never accumulated in low-lying basins. The observed geology is consistent with limited outgassing on Mars, equivalent to an amount that would cover the surface to a depth of some tens of meters at most, and with the conclusion that it never rained on the planet. Yet some mechanism for the recharge of the global ground water system is suggested, although the hydrologic system may be very different from the terrestrial one (e.g., Clifford, 1980). The development of integrated dynamic and time-stratigraphic models for the release, transport, and accumulation of fluid and associated sediment in the major channels should be given high priority. Even more important is the total integration of valley networks and channels into a general understanding of dissection, denudation chronology, paleoclimatology, and tectonic history on Mars. Comprehensive studies are needed to relate Mars' fluvial history to the planet's climatic past and to the evolution of its atmosphere.

#### **2.6. Mass Movement**

Mass movement is one of the most universal geologic processes operating on planetary surfaces. Rock falls, landslides, and creep are evident in most crater walls, and debris flows, rock slides, and

slumps have been identified on the Moon and Mars and probably occur on many other planetary bodies. Mass movement may occur on any slope where the force of gravity exceeds the cohesive strength of the surface material. It operates regardless of the presence or absence of water, atmosphere, or tectonic activity. The style of mass movement, however, and the role it plays in shaping the surface features of a planet depend on the nature of surface materials and variables such as the degree of saturation of pore space with fluids, etc. Many of the variables affecting mass movement on Earth (where water is the dominant pore fluid) have been studied thoroughly with reference to slope stability and engineering problems. In order to understand mass movement on other planetary surfaces, the basic factors that control the process must be identified and their relative importance ascertained under specific environmental conditions.

Among the more significant factors affecting mass movement in Earth's system are steepness of slopes, strength of surface materials, presence of pore fluids, weakening of surface material by shock, alternating cycles of freezing and thawing, stratigraphic and structural relationships, and the size and shape of particles that constitute surface material. Some of these factors apply to mass movement on all planets, whereas others may be important only under special conditions that exist on a specific planet. Therefore, it is probable that much can be learned about the mechanics of the process by a comparative study of mass wasting throughout the solar system.

#### ***2.6.1. Mass Movement on Earth***

On Earth, a variety of types of mass movement are recognized on the basis of (1) rate of motion, (2) kind of motion, and (3) material involved. The more significant types include (cf. Carson and Kirby, 1972) rock falls, rock slides, debris slides, debris flows, creep, block slides, slumps (landslides), solifluction, rock glaciers, and subaqueous sand flows. The presence of water at Earth's surface is perhaps the most important single factor influencing mass movement. In this respect Earth is unique among the planets. Mass movements on Earth are relatively small compared to some that have been observed on Mars (Carr, 1981). Few terrestrial landslides exceed 10–15 km in length, and many are so small that they are difficult to observe even on high-resolution aerial photographs.

### ***2.6.2. Mass Movement on the Moon and Mercury***

The Moon exhibits a variety of types of mass movement (Lindsay, 1976). Slumping of the inner walls of craters displays many of the classical features of slump blocks on Earth. In addition, some craters show flow features that suggest downslope movement of regolith. On steep slopes, features similar to rock falls and avalanches are apparent. Also, tracks and scars resulting from boulders rolling and sliding downslope have been identified in many areas.

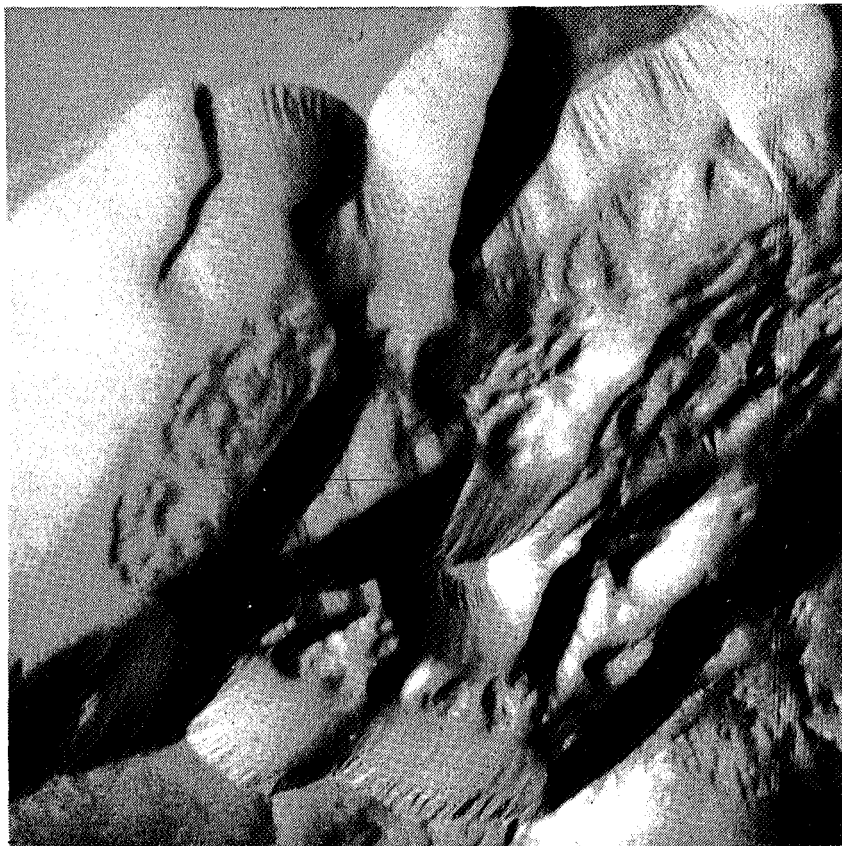
On the Moon as on other bodies that lack atmospheres and active tectonic systems, impacts are the major disturbing forces producing mass movement. Some of the unanswered questions concerning mass movement on the Moon include the following: (1) What is the role of mass movement in effacing small craters on slopes in the lunar highlands? (2) Does the cumulative effect of numerous small impacts exceed that of the rarer large events in inducing mass movement? (3) Have slopes on the lunar surface reached a state of equilibrium? (4) To what extent does slope retreat occur on the Moon?

Although crustal materials on Mercury and the Moon are approximately similar, gravity on Mercury is about twice that on the lunar surface. Thus, it would be informative to compare analogous expressions of mass movement on the two bodies. Unfortunately, the best images of Mercury have resolutions no better than 0.5 km, making such comparisons impossible at present. Nevertheless, the coverage does contain evidence of mass movement: slump terraces on the inner walls of craters and on the faces of escarpments. Significantly perhaps, no mass movement features comparable in scale to the largest such features on Mars have been detected on Mercury. Although both planets have similar surface gravities, the martian regolith may well be saturated locally with ice, whereas that of Mercury is almost certainly dry.

### ***2.6.3. Mass Movement on Mars***

The surface of Mars shows abundant examples of mass movement, many of which are enormous compared to those on Earth. Huge landslides occur within large impact craters, in Valles Marineris, and on the flanks of the large volcanoes (Sharp, 1973; Lucchitta, 1978; Carr, 1981). Spectacular longitudinal troughs and ridges on the lower parts of many landslides, as well as the backward rotation of slump blocks, are clearly seen. In addition, debris





*Mass wasting on Mars.*

flows along the regional escarpment, separating the southern highlands from the northern plains, show long flow lines. Important questions concerning mass movement on Mars include the following: (1) Why are some of the features produced by mass movement so large? (2) Is the melting of subsurface ice involved in some of these flows? (3) What is the relation of the chaotic terrain and the catastrophic floods believed to have produced the major channels?

#### ***2.6.4. Mass Movement on Other Bodies***

The Galilean satellites present some interesting new problems in understanding mass movement as a planetary process. Callisto, Ganymede, and Europa are icy bodies that have comparatively low relief, probably due to plastic flow of the ice that makes up their

crusts. On Callisto, mass movement may be represented by deposits along scarps in the Valhalla ring system. On Ganymede mass movement may be involved in the evolution of the grooved terrain by filling of extension fractures and graben. Prominent scarps exist on Io, and mass movement must occur on the surface of this sulfur-covered satellite. Many of the icy satellites of Saturn are now known to have rugged surfaces that exhibit high relief. What types of mass movement occur on their cold, icy surfaces? Unfortunately, at present we lack the high-resolution images needed to address these questions, but in the case of the Galilean satellites at least, such data should be provided by the Galileo mission to Jupiter.

#### ***2.6.5. Summary***

Mass movement is one of the few universal geologic processes operating on planetary surfaces. We know from studies on Earth that perhaps the single most important factor influencing mass movement is the presence of water. Water infiltrates the pore space, acts as a lubricant, and adds weight to the slope material. Another factor is alternating freezing and thawing, which rapidly breaks down the solid rock into angular fragments. Yet in the surfaces of other bodies of the solar system (with the possible exception of Mars), water does not exist in a fluid state. One of the more significant problems is to determine how features produced by mass movement on other planetary bodies (especially the Moon and Mercury) can resemble those on Earth without the presence of air and water. In the absence of water, what are the most significant factors affecting mass movement? What role does temperature play in mass movement on the icy planetary bodies? Is mass movement an important surface process on small bodies such as asteroids, comets, and small satellites? Evidence of mass movement on the two tiny satellites of Mars has already been detected (Thomas and Veverka, 1980) even though surface gravity is only  $10^{-3} g$ .

There is also the important question of slope retreat. On Earth, slope retreat is intimately associated with a drainage system. The slope can be thought of as an open system with a major input of material from the steeper slopes, movement of material downslope, and removal of material by the drainage system. How does slope retreat operate on Mars or Io, where gigantic scarps are known to exist? What role does sapping play in slope retreat on Mars? Do martian winds accelerate this process?

## 2.7. Glacial and Periglacial Processes

This section deals with planetary surface features and processes associated with cold regions and ice, and unless noted otherwise, the word ice refers to water ice throughout. Because the terminology involved is often misunderstood, this section begins with a review of definitions (from Gary et al., 1972):

*Glacier:* a mass of ice formed by the compaction and recrystallization of snow moving downslope or outward in all directions due to the stress of its own weight and surviving from year to year.

*Periglacial:* refers to processes, conditions, areas, climate, and topographic features in cold regions or in any environment where frost action is important.

*Permafrost:* refers to surface and near-surface materials in which the temperature is below freezing for more than a few years. The definition is based exclusively on temperature, and disregards the texture, degree of compaction, water content, and lithologic character of the material.

*Ground ice:* all ice occurring below the surface, regardless of origin or form.

A review of the various environments in the solar system shows that all planets and satellites except Venus experience temperatures below freezing. Glacial and periglacial processes definitely occur on Earth and on the icy satellites of the outer planets. On Mars, ground ice almost certainly exists, and periglacial processes probably play a major role in the evolution of the planet's surface.

### 2.7.1. Physical Properties of Water Ice of Interest to Geology

Water ice is a major constituent of many solid bodies found beyond the asteroid belt. Yet all of our knowledge about the natural properties of ice comes from observations under terrestrial conditions (e.g., Mellor, 1964). Data on the physical properties of natural ice at higher pressures and lower temperatures than encountered on Earth's surface are urgently needed (Parmentier and Head, 1979a). Some information on density, strength, rheology, and thermal behavior is available from laboratory experiments; other data must be estimated by extrapolation.

Pure water ice occurs in a wide range of polymorphs (Glen, 1974, 1975), designated Ice-I through Ice-IX. Ice-I occurs naturally on Earth and presumably Mars and many of the outer planet satellites. Ice-II, -III, -V, -VI, and -VII have been formed in the laborato-

ry at pressures greater than  $2 \times 10^3$  bars. Ice-IV, -VIII, and -IX are considered metastable phases. High-pressure forms of ice are presumed to exist in the interiors of large icy satellites, and a knowledge of the physical properties of these polymorphs is essential to a more complete understanding of the evolution and surface history of these objects.

The density relation of pure water and Ice-I is anomalous. Pure water expands about 9 percent upon freezing, and this expansion can set up large stresses at the margins of a constrained body of water such as an aquifer or a filled crack. The expansion also results in a significant decrease in density, from about  $1.0 \text{ g cm}^{-3}$  at  $4^\circ\text{C}$  to  $0.92$  at  $0^\circ\text{C}$ . Thus, the freezing of water can lead to a gravitationally stable configuration consisting of low-density ice floating on top of liquid water. If the surface of such an ice layer were to be covered by silicate material derived from meteoritic impact, for example, the density could increase sufficiently for foundering and sinking of the ice to occur (Parmentier and Head, 1979b). In contrast to Ice-I, the high-pressure polymorphs all have specific gravities greater than that of pure water. Formation of Ice-I at depth in a planet's interior could lead to the rise of diapirs to the surface.

The thermal properties of Ice-I and water are also unusual. The specific heats of water ( $1 \text{ cal g}^{-1}$ ) and Ice-I ( $0.5 \text{ cal g}^{-1}$ ) as well as the latent heat of fusion ( $79.7 \text{ cal g}^{-1}$  at  $0^\circ\text{C}$ ) are abnormally high (Fletcher, 1970). Hence water or ice in a system may act as a heat sink, modulating wide fluctuations in temperature within large bodies of ice or water. In addition, the melting point of Ice-I decreases as pressure increases. This mechanism is considered responsible for regelation, a process by which solid particles can pass through ice. Sufficient pressure on one edge of a solid particle, usually due to its own weight, lowers the ice melting point and causes melt water to flow from the leading to the trailing edge of the particle, where it refreezes in the lower-pressure region.

Mechanical properties of polycrystalline ice depend on the orientations of individual crystals. On Earth, polycrystalline ice has three main structural forms: (1) randomly oriented, (2) columnar with c-axes perpendicular to column length, and (3) columnar with c-axes parallel to column length. In addition, many complex shapes, orientations, and arrangements of crystals exist in highly stressed regions of ice. Some mechanical anisotropies are inherently associated with the hexagonal structure of individual Ice-I crystals. Bulk properties such as elastic moduli may be calculated fairly accurately

by averaging the moduli of individual crystals. Other rheologic properties of polycrystalline ice are strongly anisotropic, and averaging of individual crystal properties may not be valid.

Surface features on an icy or ice-saturated body result largely from processes of flow and fracture. Although ice is often modeled as a Newtonian viscous fluid, experiments indicate that it is more properly considered a power-law or pseudoplastic fluid that deforms by creep (e.g., Glen, 1974, 1975). In a Newtonian fluid, the rate of strain is linearly proportional to the applied stress, and the viscosity is the ratio of strain proportional to the stress raised to some power, so that as the stress level is increased, the material deforms more and more rapidly. The result is that a power-law fluid like ice appears to become less viscous at higher rates of strain. Ice-I has a power-law exponent of about 3.1 measured for stresses in the range of 10 to 100 Pa (Glen, 1974, 1975); similar data for high-pressure polymorphs are not yet available. The viscosity of ice at a given stress level decreases with increasing temperature. Thus, in the presence of a thermal gradient, the viscosity will decrease with depth. Ice also has a yield strength, a level of stress that must be exceeded before any permanent deformation can occur. Generally, this strength is so low that it can be ignored.

Under very rapid strain rates, such as during an impact event, ice behaves more like a brittle elastic material than a fluid and may be assigned a tensile strength. The tensile strength of Ice-I increases slightly from about 12 bars at 0°C to about 16 bars at 40° C (Croft et al., 1979). These values compare with about 75 bars for granite to a few hundred bars for basalt. The tensile strength of ice-saturated sand is less than that of pure ice near the freezing point, but becomes much greater at lower temperatures ranging from around 3 bars at 60°C to an extrapolated value of 50 bars at -40°C. Thus, ice will tend to fracture easily under surface and near-surface conditions of Earth and Mars, but should become quite strong at the very low temperatures that prevail on the surfaces of bodies in the outer solar system.

The above discussion has summarized some of the physical properties of pure water ice that are of major interest to the planetary geologist. A fundamental complication is that the ice encountered on any real surface will seldom, if ever, be pure. As already indicated even small amounts of impurities affect some of the physical properties of ice (e.g., its strength) quite drastically.

### ***2.7.2. Ice Masses in the Solar System***

In this section we consider ice masses on planetary surfaces and for simplicity subdivide these into glaciers (originating at least partly on land from precipitation) and floating ice (derived primarily from bodies of liquid water).

#### ***A. Glaciers***

On Earth, glaciers are classified as either valley glaciers (or Alpine glaciers) if they occupy valleys within mountains or as ice sheets (also called continental glaciers or ice caps) if they are large masses not contained by valleys. Most glaciers of both types are composed of two parts, an accumulation area where snowfall exceeds melting each year and a wastage area where melting exceeds snowfall; the volume gained and lost in these two areas constitutes the "glacial budget" as described by Sharp (1960) and determines whether the glacier will advance or "retreat." All glaciers move downslope or outward, and a "retreating" glacier simply means that the melting and ablation in the wastage area exceeds the rate of forward movement by the glacier.

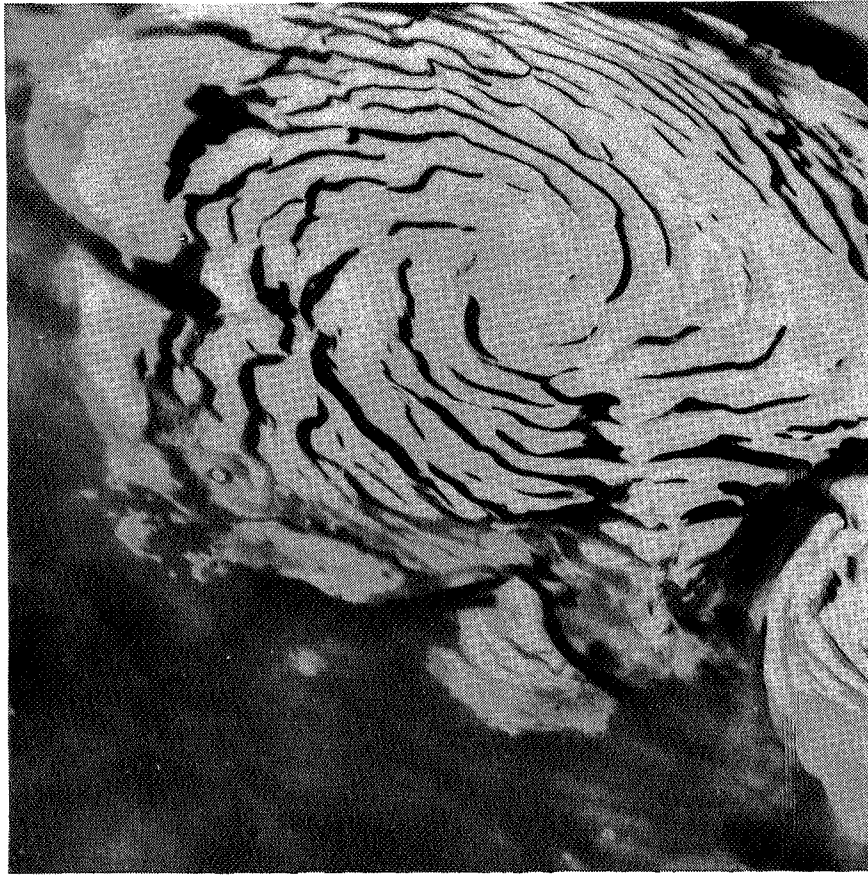
On Earth, precipitation of snow in the area of accumulation forms a deposit that is about 20 percent ice and 80 percent air. Melting and refreezing plus compaction converts the snow to spherical ice particles called firn. As the firn accumulates, further compaction causes a recrystallization to form the main ice mass of the glacier that typically has less than 10 percent air.

Movement of terrestrial glaciers occurs through three mechanisms: (1) slipping of the mass over the surface; slipping is usually lubricated by a melt water layer between the ice and the ground, (2) plastic flow (ice is a viscous medium), and (3) fracturing and sliding, in which blocks of ice in the brittle parts of the glacier break apart and move forward; this occurs principally on the surface and along some edges of the glacier. Movement of the ice mass is seldom uniform in either space or time, and differential deformation leads to surface features, some of which are large enough to be observed on aerial photography. The principal surface features are crevasses, which are elongated cracks. Crevasses are subdivided into various types as functions of their geometry and mode of origin. Some of these patterns can provide clues to the deformational history of the glacier.

Most glaciers incorporate rocky materials within the ice mass. This material can include dust and other airborne particles, as well as chunks of rock gouged by the ice as it moves across a surface or from the accumulation of debris that falls onto the glacier from valley walls. Surface material often coalesces into medial moraines that show as dark parallel stripes reflecting flow by the glacier. On Earth, material carried by the ice eventually reaches the melting front of the glacier, where it is released. It may be deposited in situ, or carried away by melt water. The finer material is often picked up by the strong winds generated along ice margins. At least some loess deposits (windblown silts) are considered to have glacier origins. Coarse glacial deposits, termed drift, may assume a wide range of geometries that can be used to interpret the form and position of glaciers after the ice mass has "retreated."

On Earth, glaciers have effected extensive changes in the landscape. U-shaped valleys, grooves, and striations parallel to the flow of ice, and amphitheater-shaped cirques in the headward parts of valleys are indicative of glacial erosion and can be seen on aerial and orbital images. In our solar system only Earth and Mars (and possibly Titan and Triton?) can have glaciers originating at least in part from precipitation. Features similar to ice sheets definitely occur in the polar regions of Mars: the permanent or residual ice caps (Murray et al., 1972; Cutts et al., 1976; 1979). Although valley glaciers have not been found on the planet, some of the high-latitude surface features may in part owe their existence to past glacial processes. At lower latitudes there are numerous channels (section 2.5) that have been interpreted by some investigators as having been cut by ancient ice streams associated with ice sheets (Lucchitta et al., 1981).

Most satellites of the major planets have surfaces dominated by ice, making glacier-like activity a possibility insofar as the relaxation of crater topography is concerned. Theoretical considerations of the rheology of ice indicate that static loading, such as in crater walls, could cause movement when the strength of the ice is exceeded; observed surface temperatures for the larger Jovian satellites (Ganymede and Callisto) imply that topographic relief should be modified noticeably by relaxation within about  $10^6$  years (Johnson and McGetchin, 1973). Voyager images reveal both fresh, normal-appearing craters and circular features ("palimpsests"), suggesting that some craters "relaxed" and flowed, whereas others have re-



*The north polar cap of Mars.*

mained preserved (Smith et al., 1979b). In ice, the relaxation time of topographic features is very temperature dependent due to the strong dependence of viscosity on temperature (Parmentier and Head, 1979b); thus, the gradual cooling of crustal temperatures could explain the nonrelaxation of more recent craters (Reynolds and Cassen, 1979). Statistical studies of craters and palimpsests can be used to infer the thermal history of the crust of an icy satellite (Phillips and Malin, 1980; Passey and Shoemaker, 1982; Passey, 1983).

#### *B. Floating Ice*

On Earth, ice that forms from freezing of liquid water includes both sea ice and ice on fresh water bodies; both are generally referred to as floating ice (Weeks and Assur, 1967; Weeks, 1967). A



wide range of surface features can form on floating ice, depending on the freezing sequence and the influence of exogenic processes such as deformation by winds.

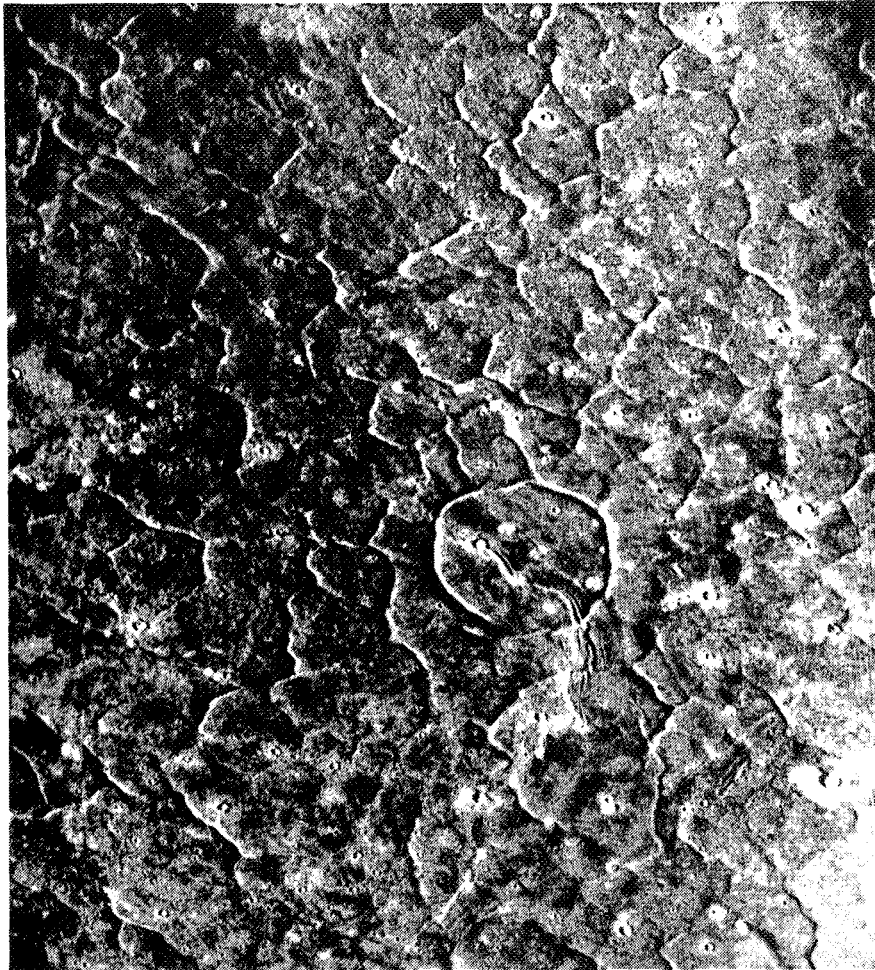
Many of the deformational features observed in floating ice may be analogous to features observed on some of the icy satellites, most notably Europa. The most common deformational surface features on sea ice are linear arrays of broken ice called pressure ridges. Ridges may form either from shear when two adjacent ice flows move parallel to one another along fractures or cracks, or from the collision of two ice floes moving toward one another. Ice ridges are composed of blocks of fractured ice. Voids between the blocks can cause the densities of the ridge to be less than that of solid ice. The porosity of the ridge in the initial stages of formation varies from 10 to 40 percent.

### ***2.7.3. Periglacial Processes on Planetary Surfaces***

On Earth, the term periglacial refers to a specific climatic zone (Davies, 1969) in which the processes of solifluction (the slow, viscous, downslope flow of water-saturated, unconsolidated materials), gelifluction (the flow of ice-saturated materials; Washburn, 1980), and nivation (the erosion of rock or soil by snow and ice, by frost action, and by chemical weathering) are characteristic, and within which such geomorphic features as permanently frozen ground (permafrost), patterned ground, and thermokarst topography are readily developed (Stearns, 1965, 1966). The occurrence of a periglacial region is not genetically related to the proximity of glaciers or continental ice sheets, contrary to what is implied by its etymology (e.g., Washburn, 1980). This broader definition is useful in that it allows us to consider the possible operation of periglacial-type processes on the surfaces of other objects in the solar system.

#### ***A. Inner Planets***

The presence and action of water are essential for most periglacial processes to occur. Destruction of lithified and unconsolidated material by nivation, the transport of this material by solifluction or gelifluction (mass wasting), and the subsequent sorting and redistribution by freeze-thaw mechanisms to form ice wedges, pingos, ground ice, and patterned ground are all characteristics of a relatively wet environment. On Earth, the resulting morphologies are generally well studied (e.g., King, 1976), but the extension of these



*Large-scale polygonally patterned fractures in the northern plains of Mars.*

terrestrial processes and landforms to other planetary surfaces is a broad topic of current interest.

The possible existence of water ice in nearly permanently shaded regions at high lunar latitudes has been suggested by Arnold (1979). Extensive permafrost-bearing plains units have been inferred for Mars, particularly in the northern latitudes (Carr and Schaber, 1979). This deduction is based on observation and interpretations of mass wasting, some types of polygonally patterned ground, and the radically striated, apparently fluidized ejecta blankets surrounding many craters. Some of these landforms appear to

be more highly developed in the higher latitudes and lower elevations, where the amount of water is inferred to be greater.

Photogeologic study of possible martian periglacial landforms is an integral part of the study of Mars and provides insight into basic physical processes that act on the planet's surface. Detailed study of terrestrial periglacial features provides the "ground truth" necessary for more efficient analysis of both the landforms themselves and the related planetwide processes on Mars. Some of these processes include water redistribution among regolith, polar deposits, and the atmosphere; of subglacial and subaqueous volcanics; phreatomagmatic eruptions and the production, deposition, modification and redistribution of pyroclastic deposits; and mass wasting and rheology of crater ejecta deposits formed from volatile-rich materials. On the other hand, knowledge gained from the Mars Viking Orbiter data may prove useful in interpreting Landsat images of the periglacial, high-latitude regions of Earth.

#### *B. Outer Planet Satellites*

The Voyager 1 and 2 encounters with Jupiter in 1979 provided a wealth of information about the four Galilean satellites, Io, Europa, Ganymede, and Callisto. With the exception of Io, all are considered to have complex icy crusts that may contain sizable fractions of silicates. Thus, the intriguing possibility exists for mass wasting and surface modification processes similar to those in terrestrial glacial and periglacial terrains. A major problem is the low resolution of available images, in which features smaller than about 500 m cannot be recognized.

Many of the Saturnian satellites imaged by Voyager are topographically rugged (Smith et al., 1981). However, periglacial and associated mass wasting processes could be inhibited by the cold surface temperatures ( $<100$  K) and the low gravitational accelerations on these satellites.

#### **2.7.4. Summary**

Processes similar to glacial and periglacial processes on Earth probably occur on other solid bodies in the solar system. In all cases studied to date, water ice is the important ice. Therefore, those physical properties of water ice of fundamental interest to planetologists must be determined, especially under conditions that pertain to studies of outer planet satellites (at low temperatures for

surface studies; at high pressure for interior models). The effects of impurities (other ices or silicates) on these properties are of crucial importance.

Studies of the behavior and surface morphology of glaciers may have some significance to investigations of the polar caps of Mars and perhaps to some features on the surfaces of icy satellites. Investigations of the characteristics and surface morphology of floating ice may be of relevance to the study of those icy satellites (e.g., Europa) which, at some point in their histories, may have had liquid mantles covered by thin ice crusts.

Periglacial studies are of great relevance to Mars, where periglacial processes were dominant in sculpturing the surface in many areas, and perhaps to investigations of the surfaces of icy satellites in the outer solar system.

Although to date the emphasis has been on water ice, it must be realized that the properties of other ices (methane, ammonia, and their clathrates) will become increasingly important to planetary geology as our exploration of the outer solar system continues. By 1986 Voyager 2 will have studied the satellites of Uranus, bodies whose surfaces may not consist of water ice only. Even today we have enough precise data about Titan to suspect that its surface consists, at least in part, of frozen methane. Finally, it should be recalled that on Mars deposits of carbon dioxide frost occur at least in the annual polar caps; further investigations of the physical and mechanical properties of frozen carbon dioxide and of its clathrate form are highly desirable.



### **3 Chronology of Planetary Surfaces**

One of the major goals of planetary exploration is to determine the surface histories of the solid planets and satellites. Surface histories tell us how these bodies evolved through time and provide information on the probable causes for observed differences. To establish a surface history, it is necessary to determine the sequence of various geologic events and, if possible, their duration. Two basic types of dating are possible: absolute and relative. Absolute age dating determines the “calendar” time at which a rock, surface, or feature formed; relative age dating determines the order—but not the time—of formation.

#### **3.1. Absolute Dating**

The traditional and most reliable method of absolute age dating requires laboratory analysis of samples. Most rocks contain small amounts of radioactive isotopes, such as  $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{40}\text{K}$ , and  $^{87}\text{Rb}$ , which decay at known rates. If the rocks have remained as closed isotopic systems, it is possible to calculate their age by measuring the amount of radiogenic isotopes relative to the amount of stable isotopes now present. In practice, this procedure requires an accurate assessment of the initial abundances of the isotopes produced in the radioactive decay. The problem becomes intricate if more than one event that affected the radiogenic isotope systems has occurred during the evolution of the rock. Many rocks have complex histories, and the challenge in isotopic age determination is to unravel and date not one, but each of the events that affected their evolution.

To date, only terrestrial, lunar, and meteoritic samples have been dated by isotopic methods. The oldest terrestrial rocks, found in the Precambrian shield of Greenland, are about 3.8 billion years old. Most of Earth's surface (the ocean basins) was formed by seafloor spreading during the last 200 million years (about the last 5 percent of geologic history). Hence Earth's surface is geologically very young. In contrast, the Moon's surface is very old. The youngest extensive stratigraphic units dated by isotopic methods are the mare basalts, which range in age from about 3.3 to 3.8 billion years. Rocks recovered from the lunar highlands are even older, and ages in excess of 4.3 billion years have been measured.

The isotopic method of determining absolute age is the most accurate and desirable way of dating planetary surfaces, but collecting and returning rock samples from distant planets and satellites is a difficult and expensive endeavor. Furthermore, some surfaces, such as those of the icy satellites of Jupiter and Saturn, may not yield rocks that are datable by current isotopic techniques. On the other hand, most solid bodies in the solar system display a record of accumulated impact cratering on their surfaces. The total number of craters recorded by a surface is a measure of its age. If the rate at which craters are formed is known, then it is possible to estimate the absolute age of the surface.

The present rate of crater formation can be estimated from telescopic observations of various planet-crossing objects. These objects include small bodies of asteroidal appearance and the nuclei of comets. The population of these objects can be estimated by statistical methods from the rates at which they are discovered by systematic searches of the sky (Shoemaker et al., 1979). Using the techniques of statistical celestial mechanics, first developed by E. J. Opik (1951), collision rates with a given planet or satellite can be derived from a knowledge of the orbits of these small planet-crossing bodies. Sizes and the size distribution can be estimated using various remote sensing techniques. An assessment of mineral composition can be made from spectrophotometric observations, and plausible densities and masses can then be assigned to well-observed small bodies (chapter 7). Cratering rates are estimated from the collision rates and from the masses and impact velocities of the colliding bodies by means of either empirical crater scaling laws or by more elaborate computer calculation of crater formation (Shoemaker, 1977).

Significant uncertainties are associated with each of these steps, particularly with the assignment of masses and with the calculation of crater sizes. One vexing problem is that, although comets have been and remain important impacting bodies, our knowledge of the sizes and densities of their nuclei remains especially poor (Wilkening, 1982). Therefore, it is extremely important to obtain independent information on the present cratering rate on different planets or satellites to check and calibrate the cratering rate calculations. Fortunately, Earth provides one such check for the inner solar system. Accurate determinations of recent cratering rates on Earth are vital to the estimation of accurate absolute ages from crater densities on the terrestrial planets. The Earth-Moon system also provides the essential record needed to determine the past variation of this cratering rate (Hartmann, 1972a).

If the cratering history is known for one planet or planet-satellite system, then, in principle, it can be derived for other planets and satellites, provided that the bodies impacting the various planets and satellites are dynamically related. In the case of asteroidal bodies that collide with Earth, it has been shown that these bodies are closely related to asteroidal objects that impact the other terrestrial planets. It has also been demonstrated that the flux of comets in the neighborhood of the terrestrial planets is closely linked to their flux in the neighborhood of Jupiter (Shoemaker and Helin, 1977).

Crater densities indicate that the present rates of formation of large craters on each of the terrestrial planets and on the Moon are approximately within a factor of 2 of the present cratering rate on Earth. Ten kilometer diameter craters are produced on Earth at the rate of  $\sim 2 \times 10^{-14} \text{ km}^{-2} \text{ yr}^{-1}$  (Shoemaker et al., 1979). From the calculated present cratering rates and the observed history of cratering in the Earth-Moon system, it can be shown that the period of early heavy bombardment probably ended 3.5 billion years ago on each of the terrestrial planets (Hartmann, 1972; Soderblom et al., 1974). On Mars, the analysis indicates that volcanism and plains formation extended through much of the post-heavy bombardment period. Much work remains to be done, however, to refine the accuracy of these age estimates based on crater densities. More extensive telescopic observations are needed to improve our knowledge of the physical properties and collision rates of the planet-crossing bodies, and computer models must be refined to estimate



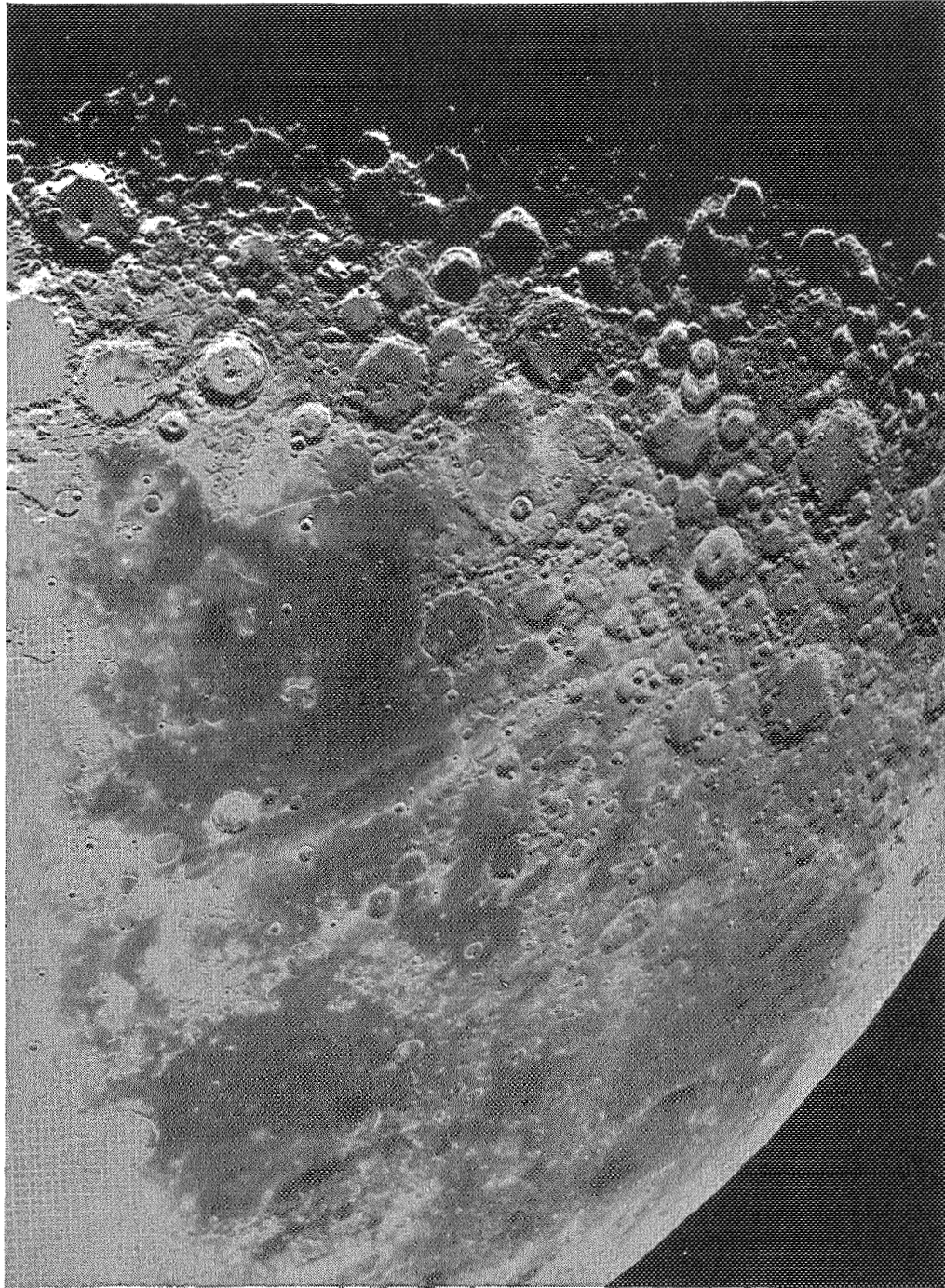
more accurately the crater sizes produced on various planetary surfaces.

Another method that has been used successfully on the Moon to estimate absolute ages involves the correlation of the morphology of small craters ( $\leq 1$  km in diameter) with the absolute age of a surface determined from isotopic measurements (Shoemaker, 1966). The technique depends on an erosion model that relates the shape of a crater to the integrated flux of meteoroids and secondary debris that have impacted the surface since the crater was fresh. The method provides a means of estimating absolute surface ages in areas not sampled by the Apollo missions and suggests that some mare regions may be as young as about two billion years.

### **3.2. Relative Dating**

Although it is not always possible to date a geologic event or surface on an absolute time scale, it may be possible to establish the order in which events occurred by the traditional methods of superposition and cross-cutting relationship among various geologic units. Material units that were deposited on other units clearly postdate the units on which they lie. For example, lava flows that are observed to embay crater rims or associated ejecta deposits were emplaced after the formation of the craters. Craters and their associated ejecta blankets that overlie these flows postdate the emplacement of the flows. Tectonic structures such as faults can be dated relative to other events by their cross-cutting relationships. For example, faults that cut the cratered highlands on the Moon but terminate at the boundary of a unit that embays the highlands indicate that a period of crustal deformation occurred after the formation of the highland unit but before the emplacement of the unit that embays it.

Another method of relative age dating involves the relative abundance of impact craters on different geologic units. This method makes no assumptions regarding the flux history of impacting objects and relies only on the principle that an older surface will have accumulated a greater number of craters than a younger one. An example is provided by the difference in the abundance of large craters between the lunar maria and highlands. The relatively high number of craters in the highlands indicates that the highland rocks are older than the mare lava flows, an observation that was confirmed by the Apollo missions. Although this method of relative age



*The striking contrast in crater abundance between the highlands and maria on the Moon.*

dating is rather straightforward, there are certain complications that must be taken into account. First, primary impacts produce large numbers of secondary craters that may be widely dispersed over the surface. The size of secondary craters depends on the energy of the primary impact and can attain diameters up to about 20 to 25 km for large basin-forming collisions. Should a significant number of secondary craters be included in a crater count, a spurious relative age will result. This problem can be minimized by counting only the larger craters and excluding obvious secondaries (those which occur in clusters or display irregular rim structure). Another potential problem is that certain geologic processes such as lava flows may leave the rims of large craters exposed. If the imaging resolution is not sufficient to determine whether or not a given crater is superimposed on a specific geologic unit, it may be erroneously included in the crater counts used to determine the relative age of this unit. Obviously, relative age dating between surfaces on different planets and satellites based on comparisons between crater abundances is not reliable without a knowledge of the orbits and the flux histories of the impacting objects and of the relative efficacy with which craters are produced on the various objects.

In summary, relative age dating based on crater abundances and on traditional superposition and transection relationships provides a powerful means of determining the sequence of events that have shaped a planet's or satellite's surface. The geologic history of a body can be reconstructed, and time constraints can be placed on its thermal history and internal dynamics.

### **3.3. Potential New Information on Solid Bodies**

In the next decade improved calibrations of the cratering time scales and new observations by spacecraft can be expected to yield major advances in our understanding of the evolution of solid bodies of the solar system. Some of the advances that can be anticipated are outlined briefly below.

#### ***3.3.1. Mercury***

No new spacecraft observations of Mercury are expected in the next decade, but significant improvements in the calibration of the cratering time scale on Mercury can be achieved. The present cratering rate on the planet is close to the current cratering rate on the Moon. Collision of long-period comet nuclei may have produced

somewhat more than half of the recent large craters and planet-crossing asteroids somewhat less than half. This proportion is slightly different than that for the Moon, but, to a close approximation, the post-heavy bombardment cratering history of Mercury is believed to have followed the same pattern as that on the Moon. Studies of the highland crater size distributions suggest that the same family of projectiles struck Mercury and the Moon during late heavy bombardment (Strom, 1979). If the history of decay of late heavy bombardment on Mercury also followed the history of late heavy bombardment on the Moon, the youngest large basin discovered, Caloris, is comparable in age to the youngest large lunar basins, Orientale and Imbrium, and all of the plains units are older than 3 billion years. Significant improvements in the calibration of cratering time scales on Mercury can be expected as our general understanding of cratering rates in the inner solar system improves through continued observational and theoretical work.

### ***3.3.2. Venus***

Existing radar observations suggest that ancient cratered surfaces may be present on Venus and that the crater populations may be roughly comparable to those of the lunar highlands (Masursky et al., 1981), although a volcanic or tectonic origin for many of the crater-like features is also possible at this stage. Ages of major features of probable volcanic origin and the broad outline of the history of volcanism on Venus could be ascertained from more detailed radar imaging data. The great Ishtar Terra plateau is evidently underlain by a thick slab of differentiated crust. Crater densities could determine the age of this feature and thus place bounds on the time at which global differentiation of Venus' crust occurred.

### ***3.3.3. Mars***

Extensive high-quality spacecraft observations are already available. Important advances in our knowledge of the evolution of Mars will come largely from further study of these data and from improvements in the martian cratering time scale. The present production of craters is dominated by shallow Mars-crossing asteroids. An intensive telescopic study of these asteroids may be expected to provide a fairly accurate cratering time scale. Present evidence suggests that the current rate of production of small (1 km in diameter) craters is about twice as high as the rate on Earth (Shoemaker et al.,

1979). Ages for the youngest lavas on Olympus Mons and on the giant Tharsis volcanoes indicated by this cratering rate are less than 10 million years. As the eruptive histories of these volcanoes span at least several hundred million years, the young ages of the lavas suggest that these features are merely dormant and that Mars is a volcanically active planet (Carr, 1981). A better calibration of the cratering time scale on Mars would not only sharpen our understanding of the time development of martian volcanism, but could also yield reliable age estimates for the various fluvial channels. However, no such calibration will be secure until samples of the Martian surfaces have been dated by isotopic techniques.

#### ***3.3.4. Asteroids***

Abundant isotopic age determinations are available for presumed asteroid fragments available to us as meteorites. The difficulty is that few (if any) meteorites can be identified confidently with a specific asteroidal parent body. Progress can be expected from theoretical studies of the dynamical mechanisms of delivery of meteorites to Earth and of the collisional evolution of the asteroids (Wetherill, 1977). Significant progress may also be made in determining the minerologic compositions of asteroid surfaces from remote sensing observations (chapter 7), thus aiding in the ultimate identifications of some meteorite parent bodies (Chapman and Gaffey, 1979; Gaffey and McCord, 1979; Larson and Veeder, 1979). However, spacecraft missions to one or more asteroids represent the next major step in unraveling asteroid histories; it may even be feasible to obtain samples from some near-Earth objects.

#### ***3.3.5. Satellites of Jupiter and Saturn***

Many of the large satellites orbiting Jupiter and Saturn are now known to have experienced complex surface histories (Smith et al., 1979b, 1981). Io, the innermost large satellite of Jupiter, has the highest rate of volcanic activity of any body in the solar system. Europa and Ganymede have been largely resurfaced by mechanisms that probably involved flooding of the surface by water. A preliminary evaluation of the rate of cratering by comet impact suggests that the entire surface of Io may be no older than a million years and that the surface of Europa is less than 100 million years old. Partial resurfacing of Ganymede probably occurred near the end of a period of heavy bombardment, probably between 3.5 and 4.0

billion years ago. The largest uncertainty in the chronology of events in the Jovian satellite system resides in our estimates of the sizes and masses of impacting comet nuclei. An intensive program of photometric and radiometric observations of comet nuclei at large heliocentric distances (where comets are least active) is needed to improve our knowledge of their dimensions; the calculated cratering rates depend critically on this parameter.

The geologic histories of Saturn's small icy satellites appear to be as complex as those of the much larger icy satellites of Jupiter (Smith et al., 1981). Successive surface layers were formed on Enceladus over the span of geologic time. Tethys, Dione, Rhea, and Iapetus show evidence of internal activity, and plains-forming eruptions occurred comparatively early in the history of each body. A complex cratering record is preserved on each satellite, but two factors complicate the interpretation. First, the present cratering rate probably is dominated by Saturn-family periodic comets, the existence of which is inferred largely from dynamical theory, rather than from actual observations. These comets exist far from the Sun and Earth, and their sizes and numbers cannot be determined by telescopic studies. Second, the early cratering history may include numerous craters produced by collisions with debris in orbit around Saturn. The rates and history of cratering by this debris are not readily determined from theory. Thus, the cratering history of Saturn's satellites, a key to understanding the evolution of their surfaces, will continue to be a challenging problem during the coming decade.

### **3.4. Summary**

Dating techniques are essential to geologic studies of planets and satellites in that they provide the timing and duration of events that affected the evolution of the surfaces we see today. The most secure dating techniques remain those based on isotopic measurements, and great efforts should be made to extend these to other bodies (especially Mars). The direct dating of lunar samples refined our understanding of not only the Moon's evolution, but also of the evolution of terrestrial planets as a whole, to a degree that is impossible to overemphasize. There can be little doubt that the absolute dating of additional planetary materials would prove equally informative.

Important dating information can also be obtained from careful crater counts. To interpret such crater counts fully, however, requires information on the current and past populations of impacting bodies. Although much progress has been made in recent years in evaluating the flux of impacting objects in Earth's vicinity, too few reliable data exist for the solar system beyond the asteroid belt. Specifically, our knowledge of the numbers, and especially of the dimensions, of comets is too poor to predict accurate cratering rates in the outer solar system. This situation could be improved significantly by a concentrated program of Earth-based observations of comets. Ample work also remains to be done in refining theoretical models that seek to tie in the current flux of cratering objects to its history over the past 4.6 billion years.

The importance of reliably identifying craters on the surfaces of Venus and Titan, and thereby estimating ages, cannot be overemphasized.

## **4 Geochemistry in the Planetary Geology Context**

Within the planetary context, geochemistry is concerned with seeking answers to some very fundamental questions. Most concern the past and present states of the solar system and especially the processes that have been active during the system's evolution over the past 4.6 billion years. Examples of general questions considered by planetary geochemistry include the following:

1. What were the physical and chemical conditions in the solar nebula at the time the planets and satellites formed?
2. What was the initial chemical makeup of various bodies in the solar system?
3. What chemical and physical processes have been active in the evolutions of various planets and satellites?
4. How did the atmospheres of the Earthlike planets evolve to their present state?

To the planetary geologist, geochemistry can provide important information of two basic types. First, there is information on the present bulk and surface composition of a planet or satellite. Such fundamental data constitute important constraints in many geologic discussions concerning the evolution of a particular object. Second, there is essential information about the types, rates, and chronology of various processes that have molded the planet's surface into its present state.

Ideally, to provide the most reliable information, the geochemist will need for analysis a well-selected suite of rock samples representative of the planet's surface (and perhaps a sample of its atmosphere). Only for Earth and the Moon are such samples available. True, numerous meteorites have been studied in detail, but



here the problem is that we are not quite sure of the sampling processes or of the precise parent bodies.

Given a sample of a surface, determinations of the mineralogic and petrologic relations, along with a detailed chemical analysis in terms of major, minor, and trace elements, can be used to deduce the processes that produced the various rock types and formed the major rock units. At the same time isotope techniques can be used to date some of the major events involved. Such a comprehensive understanding of the geochemical and petrogenic processes that have operated on a planet is required if we are to develop a reliable model of the object's evolution. So far such an ambitious undertaking has been realized only for Earth and the Moon and to a much lesser extent for the various parent bodies of our meteorites. It is hoped that at least one other planet (Mars?) will be added to the list before the end of the twentieth century.

#### **4.1. Information from Sample Analysis**

Accurate compositional data are essential to fully understand the evolution of planetary bodies. Studies of the mineralogy, mineral chemistry, texture, and bulk chemical composition of rocks are necessary to define their physical and chemical histories. Evidence for processes ranging from crustal formation to chemical weathering at the surface can be investigated through such studies, which are especially important when rocks and soils have experienced sequences of complex events.

Trace element chemistry can be used to determine a wide variety of signatures of specific geochemical processes. Analyses of siderophile, chalcophile, lithophile, and volatile elements in groups or in pairs yield evidence on, among other things, the nature of the bulk starting material for planetary differentiation, the degree of differentiation, the planetary heat sources, the temperatures and pressures of internal processes, and the nature of meteoritic material impacting the planet. Such data, interpreted in conjunction with petrologic data, can unravel the complex evolutionary history of planetary surfaces.

Precise isotope analyses, which to date can only be accomplished in terrestrial laboratories, can be used to study a wide variety of chronologic and geochemical problems. Long-lived radioactive species (U-Th-Pb, K-Ar, Rb-Sr, Nd-Sm) can be used to obtain isotopic ages for rocks and to establish an absolute chronology for a

planet (Kirsten, 1978). The stable isotopes (O, Si, C, S, N, H) provide geochemical tracers that can be used in conjunction with chronologic data to give information on past states of the interior of the planet as well as more recent surface processes and atmospheric modifications (e.g., Holland, 1978). Anomalies left by the decay of extinct short-lived radioactive isotopes can provide evidence for preaccretion conditions and time scales (Podosek, 1970).

Analyses of the rare gases (He, Ne, Ar, Kr, Xe) and their isotopes provide information on the differentiation history of the planet, its interaction with cosmic radiation, and the evolution of the atmosphere. Xenon isotopes are perhaps the most versatile, as the isotopic patterns may be affected by extinct short-lived isotopes, fission of long-lived and extinct isotopes of U and Pu, as well as mixing effects with various reservoirs of gas. In situ isotopic studies of atmospheric gases can yield important clues to the evolution of a planet's atmosphere. Examples include measurements of the  $N^{14}/N^{15}$  ratio in the atmosphere of Mars (McElroy et al., 1976) and of the H/D ratio in the atmosphere of Venus (Donahue et al., 1982).

Rocks can also be examined for evidence of remanent magnetization, a clue to the history of the planet's magnetic field, and for a variety of physical properties, such as density, porosity, thermal conductivity, and seismic wave velocities, which are essential to complement the geophysical measurements that can be made from orbit and from surface stations. The physical properties of surface materials must also be understood in order to determine their capacity to adsorb and release gases and to quantify the rates of gas interchange with the atmosphere (Fanale and Cannon, 1974).

The study of returned samples provides an excellent opportunity for the detection of evidence of past or present life. In order to preserve the integrity of information contained in the returned sample, sterilization (by whatever means) should be avoided.

#### **4.2. Information from Atmospheres**

Planetary atmospheres are mixtures of gases and aerosols retained by the planet's gravitational field. Within the context of planetary geoscience, atmospheres are studied for information about the composition, origin, and evolution of a planetary body. They provide information about the planet's chemical and isotopic composition and about the extent and chronology of outgassing. Relevant questions include the following:

1. How and when did the atmosphere form?
2. What was the initial composition of the atmosphere, and how is it related to that of the planet?
3. Has the composition of the atmosphere changed with time? If so, what processes modified the composition? When did the modification occur? Are the modification processes related to planetary differentiation?

Planetary atmospheres vary considerably. The massive atmospheres of the giant planets have changed little since the formation of the solar system. The terrestrial planets have weaker gravitational fields and cannot retain light gases. Even if these planets once had atmospheres of primitive solar nebula composition, the light gases would have been lost quickly (Hunten, 1973; Pollack and Yung, 1980).

The nature of the initial atmospheres of the terrestrial planets is related to the mode and timing of planetary formation and differentiation (Turekian and Clark, 1975; Pollack and Yung, 1980). If the planets formed cold before the solar nebula dissipated, then their primitive atmospheres would have consisted of the noncondensed solar nebula minus the light gases. If the planets formed hot, then the products of outgassing from the condensed solar nebula materials must be added to the primitive atmosphere. If the planet formed after the solar nebula was dissipated, then the initial atmosphere would consist only of the products of outgassing from the condensed solar nebula materials minus the light gases. If the early Sun went through a T-Tauri phase, then a part of the primitive atmosphere may have been lost from the terrestrial planets.

Processes that change the composition of a planetary atmosphere include both those which add material and those which remove it. The former includes capture from the primitive solar nebula, capture from the solar wind, additions during late-stage accretion, additions during later collisions with comets and meteorites, accumulation from outgassing of the planetary interior, accumulation from biologic activity, and accumulation from chemical reactions with surface materials. Processes that subtract material include escape to space (by blow-off or thermal escape), consumption by chemical reactions with surface materials, and escape by ionization and subsequent electromagnetic acceleration by the solar wind. (In the presence of a sufficiently strong planetary magnetic

field, the upper atmosphere is protected from ionization and subsequent removal by the charged particles of the normal solar wind.) Most of these removal processes were probably very active during the early histories of the terrestrial planets and eliminated virtually all traces of the primitive atmospheres.

What factors determine the composition and evolution of the atmosphere of a planet such as Earth? Certainly one of the most important factors is the volatile content of the planet. This, in turn, is thought to be partly a function of the position (temperature) within the preplanetary nebula at which the material comprising the object condensed (Lewis, 1974). However, it is possible that volatile-rich objects such as comets have altered some volatile inventories (Anders and Owen, 1977; Chang and Kerridge, 1982). A second factor is the thermal history of the object. It determines whether volatiles present in bulk have been transferred to the surface. The object's thermal history is, in turn, mostly determined by the amounts of accretional (impact) energy added to the growing planetary nucleus, as well as energy from both short- and long-lived radionuclides, and in special cases, even tidal energy. In the most general terms it is the size of an object that determines its energy history; large objects accumulate more gravitational heat and retain energy longer than small ones. Of course, a small object can have an active degassing and differentiation history under special circumstances. A general principle, however, is that, except for the tidal heating, continuing or increasing degassing after billions of years is more likely for large objects than for small ones. General discussions of thermal evolution are given by Toksoz et al. (1978) for rocky objects, and by Parmentier and Head (1979b) for icy ones. A third factor is that once degassed, planetary volatiles can react chemically with primary igneous rocks to form alteration products such as clays and carbonates. Additionally, such volatiles can be incorporated physically into a planetary regolith (usually in a frozen or adsorbed state). A fourth major factor affecting inventories of volatiles is loss to space. Loss to space can be very selective by mass; preferential loss of hydrogen can convert a reducing atmosphere to an oxidizing one. Planetary escape is a complex process (e.g., Hunten, 1973; Pollack and Yung, 1980) and may involve other mechanisms than blow-off or simple Jeans escape.

Differences in the surface volatile inventories of solid bodies in the solar system can be understood largely in terms of these four

factors: initial bulk volatile content, degree of outgassing, reaction of atmospheric products with surface material, and escape to space. As far as bulk volatile content is concerned, it is likely that solar-system-wide compositional gradients exist. For example, in one hypothesis, the center of the solar system represents a heat source that prevented condensation of volatile and semivolatile elements and compounds in its inner portions prior to gas dispersal. Thus, a single compositional gradient radial to the Sun could describe the resulting array of solid planetary bodies: the outer objects being more volatile rich. Specific compositional predictions have been published, most notably by Lewis (1974), Grossman (1972), Grossman and Larimer (1974), and others.

Although remote sensing of planetary atmospheres is a well-developed science, many of the characteristics of atmospheres are determined most reliably from analyses done in situ. The atmospheres of Earth, Venus, and Mars have been sampled directly, and Galileo is expected to sample the atmosphere of Jupiter in the late 1980s. Once the detailed composition of an atmosphere is known, studies of surface samples can provide valuable constraints on the history of atmosphere/crust interactions. Martian surface materials could provide evidence for a previous "wet" regime on Mars; samples of the venusian surface could provide information on the importance of such reactions as  $\text{CaMgSi}_2\text{O}_6 + \text{CO}_2 \rightarrow \text{MgSiO}_3 + \text{CaCO}_3 + \text{SiO}_2$ , which might be buffering the partial pressure of  $\text{CO}_2$  in the atmosphere to some extent.

### 4.3. Geochemical Clues to Surface Processes

The many processes that affect the surfaces of planetary bodies are outlined in chapter 2. Such processes are commonly characterized as either internal (endogenic) or external (exogenic). For planets with atmospheres, there is a special class of exogenic processes (eolian, fluvial, and chemical weathering) that depend on the interaction of the surface with the fluid atmosphere/hydrosphere.

Some surface processes, such as weathering, erosion, transportation, deposition, and lithification, are universal to all solid-surface planetary bodies. However, their relative intensity varies depending on local conditions, and in simplest terms one can define the following two broad categories: (1) surface processes on planets with atmospheres and (2) surface processes on bodies with no atmospheres.

#### ***4.3.1. Surface Processes on Planets with Atmospheres***

For this class of objects, which includes Earth, Mars, Venus, Titan, and perhaps Pluto, the essential questions are:

1. To what extent does the atmosphere shield the surface from direct bombardment by external material? How have the effects of impacts been modified by other surface processes?
2. What is the nature and extent of physical and chemical weathering?
3. How is material eroded, transported, deposited, and lithified? What agents are available? What evidence of their relative effectiveness is present?

Weathering of surface materials may result from both chemical and physical interactions with the gases and liquids of the atmosphere and, in the case of Earth, the hydrosphere and biosphere. The net result of chemical weathering is a modification of the original surface and the production of secondary materials. Physical weathering modifies the original surface material primarily by fragmentation processes that increase the fraction of fine-grained relative to coarse-grained material. The interaction of chemical and physical processes is complex; for example, fragmentation processes increase the surface-to-volume ratio of an assemblage of particles, rendering them more susceptible to chemical reaction; physical separation of light from heavy minerals may allow the preferential chemical or physical destruction of one in favor of the other. The physical and chemical processes operating on a given planetary surface can be understood and evaluated only if the composition, pressure, temperature, and dynamic processes of the atmosphere, as well as the composition of the surface materials and the crustal processes acting on these materials, are well determined.

When products of weathering, erosion, transportation, deposition, and lithification are preserved, they contain a historical record of a planet's climate, atmosphere, volcanism, and tectonism. Before these records can be deciphered, an adequate description and understanding of surface processes is essential (see chapter 2).

All planetary objects are continuously bombarded by electromagnetic radiation, solar wind electrons and ions, and highly energetic galactic cosmic rays. Solar electromagnetic radiation heats the atmosphere and is the major driving force for atmospheric circulation producing erosion by wind. The products of the interaction of

solar and galactic particles with planetary atmospheres and surfaces may also be utilized to characterize various planetary processes ranging from atmospheric mixing to deposition rates of surface materials.

All planetary bodies are subject to meteoritic bombardment. The presence of an atmosphere places a lower limit on the size of a meteorite that can impact the surface. In general, the lower limit varies inversely with atmospheric density, which in turn may vary with time (Kahn, 1982). For present atmospheric densities, for example, a meteorite initially weighing 1.0 kg will not reach the surface of Earth but can impact the surface of Mars.

#### ***4.3.2. Surface Processes on Bodies with No Atmospheres***

This category includes the Moon, Mercury, most satellites, and all asteroids. The key questions include:

1. How did meteoroid bombardment affect the early evolution of the crust?
2. What is the extent of weathering, erosion, transportation, deposition, and lithification due to both external and internal processes?
3. How do electromagnetic radiation and energetic particles interact with the surface? Can this interaction be utilized to determine surface chemistry and mineralogy (e.g., by observing emitted X-rays)?

On planetary bodies with virtually no atmosphere, the surface layer composed of impact comminuted debris, is referred to as regolith. So far the only regolith studied in detail is that of the Moon. Since the evolution of a regolith depends on numerous factors, we can expect that significant differences among planetary, satellite, and asteroid regoliths will exist. For objects with virtually no atmosphere, electromagnetic radiation, solar wind ions, and highly energetic galactic cosmic rays penetrate to the solid surface (unless some of the charged particles are deflected by a magnetic field). This bombardment produces changes in the lattice structure and composition of regolith grains, effects which have been studied extensively in lunar soils. Some of the effects of this irradiation are preserved in grain surfaces and may hold a record of past variations of solar output (Crozo, 1977). They have also been used to date lunar craters and to determine rates of regolith turnover (Langevin

and Arnold, 1977). Similar investigations could be carried out for other airless bodies once samples of their regoliths become available for study.

From the study of the Moon, meteorite impacts are known to be important agents of weathering, erosion, transportation, deposition, and lithification on a body with virtually no atmosphere. Meteorite impacts excavate and transport materials (chapter 2, section 3) and can affect profoundly the physical, chemical, and petrographic characteristics of surface materials. Moreover, large-scale cratering events may trigger igneous activity or even the breakup of crustal plates.

#### **4.4. Examples of Key Issues and Problems**

From the point of view of planetary geology, one of the essential geochemical tasks is to test the extent to which current models of the formation and evolution of the solar system and of particular planets are supported by actual observations. For example, one popular series of models, that of J. S. Lewis, L. Grossman, and others, is based on the premise that a strong radial temperature gradient existed in the preplanetary nebula. Such models predict large differences in the bulk volatile content of the Earthlike planets, with Mars being more volatile rich than Earth, and Venus more volatile poor. In some extreme versions of such models, Venus accretes at most minor amounts of water. However, recent measurements of rare gas abundances in Venus' atmosphere by the Pioneer Venus spacecraft shed some doubt on such a simple picture. The measurements indicate that Venus accreted unexpectedly large amounts of  $^{36}\text{Ar}$ . One explanation that has been offered is that the early nebula was much more isothermal (Pollack and Black, 1982) than traditional models allow. Such a conclusion, if confirmed, would affect current estimates of the initial volatile content of the Earthlike planets and of the bulk chemical composition of objects as a function of distance from the Sun.

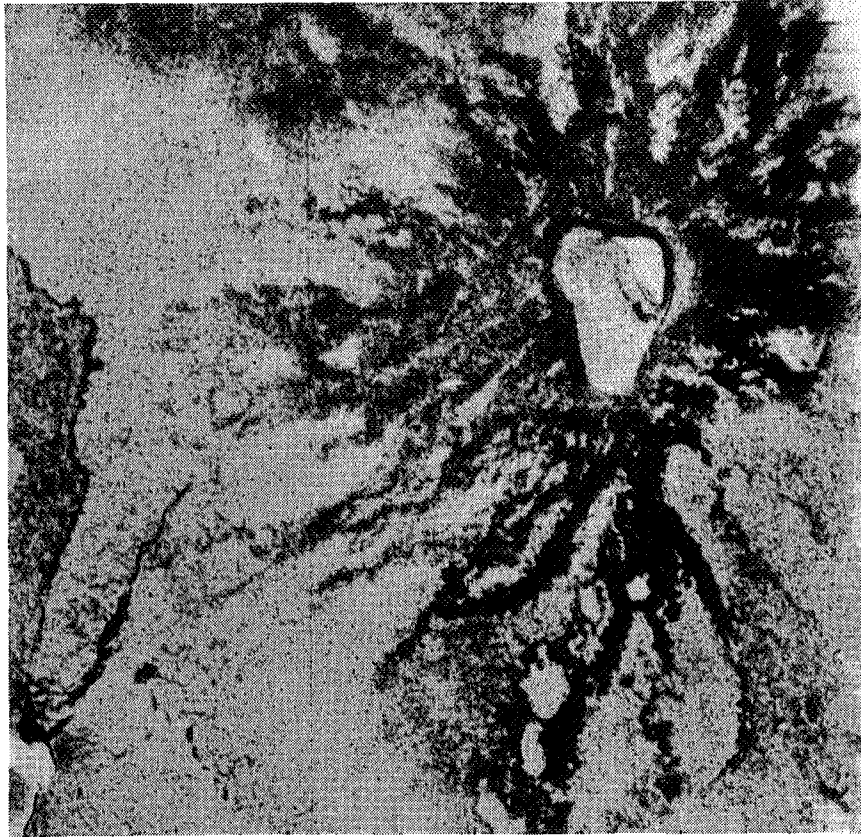
The satellites of Saturn provide another excellent example of why it is important for planetary geology to know the initial chemical composition of solar system objects. At the present time it is not clear whether small satellites such as Enceladus, Tethys, Dione, etc., contain any ices other than water ice. The issue is essential to models of their thermal evolutions, since the presence of ammonia



ice would lead to a significant lowering of melting temperatures, allowing much more vigorous tectonic histories for the same amount of heat energy. If the small Saturn satellites accreted ammonia ice (probably in the form of ammonia clathrate) in addition to water ice, then the geologic evidence of internal activity still preserved on the surfaces of Tethys, Dione, and especially Enceladus would be easier to understand (Poirier, 1982; Squyres et al., 1983).

A closely related problem involves the evolution of Titan's atmosphere. If it is true that the nitrogen that makes up the bulk of Titan's atmosphere comes from the photodissociation of ammonia, and the methane either from outgassing or sublimation from the surface, then clearly Titan accreted not only water ice, but also ammonia and methane. Whether this evidence can be used to infer that a satellite such as Enceladus accreted ices other than water ice depends critically on the temperature gradient in the vicinity of Saturn at the time of satellite formation (Pollack et al., 1976). Following Voyager, enough is known about the composition of Titan's atmosphere and the bulk composition of the satellite itself that geochemical modeling aimed at determining the state of the satellite's surface becomes possible. Available suggestions vary widely; in some schemes Titan's surface is icy; in others, it is covered at least in part by liquid hydrocarbons; still another scheme has the surface covered to great depths by complex organic material ultimately derived from Titan's photochemical clouds. Since attempts will be made to study the surface of Titan by spacecraft during the next two decades, it is essential to start thinking about the likely geologic characteristics of Titan's surface. Geochemical modeling of interior, surface, and atmospheric processes can provide valuable constraints on such speculations.

It is a truism that one cannot proceed far in geologic investigations of the surfaces of outer planet satellites without running into questions that involve geochemistry. Perhaps the most extreme example involves the surface of Io. Traditionally, the attempt has been to interpret the surficial colors, albedos, and morphology in terms of sulfur and sulfur dioxide frost, although numerous geologic and spectrophotometric difficulties with such a simple scheme are now known (Schaber, 1982; Sill and Clark, 1982). An important question that still has not been addressed adequately is the following: given that sulfur and/or sulfur dioxide are erupted onto the surface, what compounds will be preserved given realistic modeling of Io's bizarre



*Lava flows of uncertain composition (sulfur? silicate?) associated with the Maasaw Patera volcano on Io.*

environment? More important, how likely is it that the volcanic products would be pure sulfur or sulfur dioxide? What about explosive eruptions of silicate materials? Far from being a simple mixture of various forms of sulfur and sulfur dioxide frost, the surface of Io probably consists of entire suites of sulfur compounds, silicate ash, and perhaps even basaltic eruption products. The geochemical problems involved must be carefully studied, both in terms of the likely composition of erupted materials and in terms of short-term and long-term chemical alterations on the surface.

A related problem involves the contamination of neighboring satellites by materials from Io. Currently the best explanation of the red colors of Amalthea and the other small inner satellites of Jupiter and of the reddish tinge of Europa is that these surfaces are

contaminated by sulfur from Io (Thomas and Veverka, 1982; Eviatar et al., 1981). Adequate measurements of what ions exist in the vicinity of Io are available, but precise studies of how these materials would modify the regoliths of neighboring satellites are lacking.

In the inner solar system, among the most pressing geochemical problems of importance to planetary geology are those associated with the evolutions of the atmospheres of the Earthlike planets. Did Venus really outgas an ocean of water? Was the atmosphere of Mars always as thin and cold and dry as it is today? The importance of precise answers to such questions in understanding the history of weathering and other surface processes on these planets is evident.

#### **4.4.1. Venus**

We have already noted that equilibrium condensation schemes that involve a preplanetary nebula with a strong temperature gradient suggest that Venus accreted from relatively water-poor materials (e.g., Lewis, 1974), a conclusion that can be viewed as consistent with the planet's present low atmospheric water content. Yet it is equally possible that Venus lost a great deal of water through a series of processes involving dissociation, exospheric escape of hydrogen, and oxidation of the Venusian surface. In fact, if the recent models inspired by the high  $^{36}\text{Ar}$  content of the atmosphere measured by Pioneer Venus are correct, then Venus somehow lost the equivalent of an ocean's worth of water (Donahue et al., 1982). Given projected rates of water dissociation and hydrogen escape, the process could have taken as little as 100 million years. Exposing enough fresh rock to use up the associated oxygen this quickly is difficult but perhaps possible. No matter which scheme is correct, it is evident that the atmospheric environment of Venus has changed through time and therefore so have weathering and other surface processes.

Three major scenarios for the evolution of Venus' atmosphere seem plausible at present. The first possibility is that Venus outgassed only a small amount of water and that this water was quickly eliminated by the processes outlined above. The second possibility is that Venus quickly outgassed as much water as Earth and that its atmosphere rapidly reached its current greenhouse state. According to this scenario, atmospheric conditions on Venus have been similar to the present ones over most of geologic time. A third possibility is that, although outgassing of water was substantial and rapid, Venus'

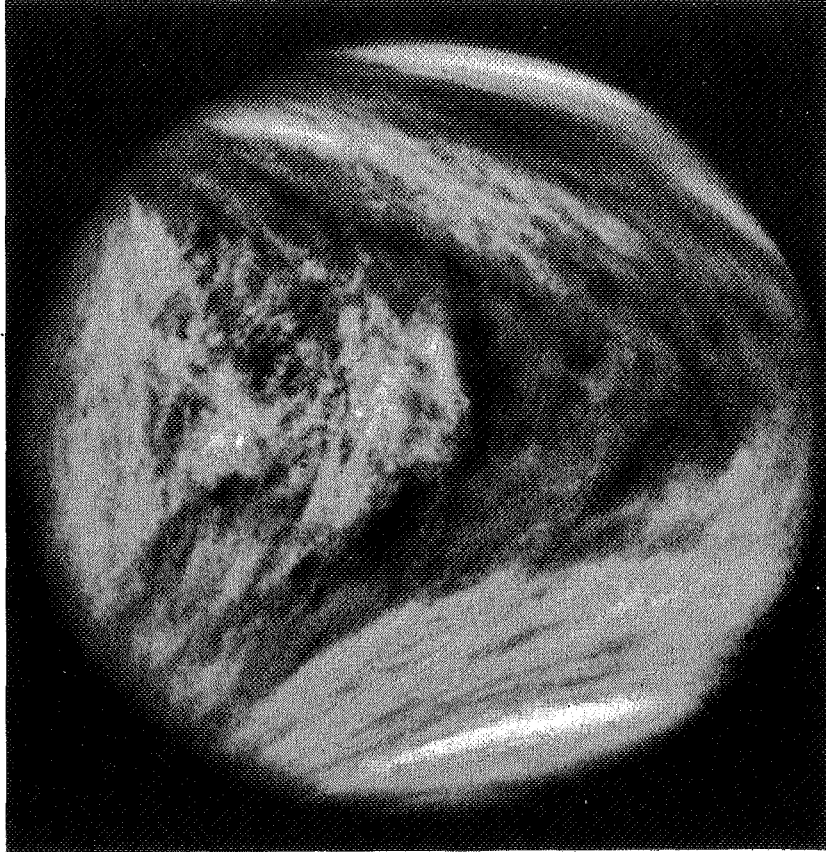
entry into the runaway greenhouse mode was substantially delayed, perhaps because the Sun was initially some 30 percent dimmer than it is today. Recent speculations (Pollack and Yung, 1980; Phillips et al., 1981) and interpretations of Pioneer Venus rare gas data and D/H measurements (Donahue et al., 1982) seem to favor models that involve losses of substantial amounts of water by the planet.

The implications for geology are profound. If Venus were cool enough at the beginning for liquid water to exist on the surface, huge carbonate deposits might have been formed. Certainly, any massive loss of water must have been accompanied by a thorough oxidation of the surface materials. If the loss of water were accompanied by a dehydration of the lithosphere, it could have led to a sudden stiffening of the lithosphere, profoundly affecting tectonic processes. Whether evidence of such a stiffening (if it occurred) is preserved in the surface morphology depends in part on when it happened and on the rate of weathering. One would expect that under present conditions (high pressure, temperature, and acidity) weathering would be rapid. However, detailed investigations of current and past weathering processes and rates are needed.

#### **4.4.2. Mars**

Mars is generally considered to be richer in volatiles than Earth, an idea consistent with the planet's lower mean density and with ubiquitous geomorphological evidence of subsurface ice (Rossbacher and Judson, 1981). Channels and valley systems (chapter 2 and Baker, 1982) provide strong evidence of climatic change, although the timing, severity, and causes of these changes remain largely unresolved. Based on interpretations of rare gas abundances in the atmosphere measured by the Viking spacecraft, it is commonly argued that Mars outgassed less material (per unit mass) than Earth; estimates vary, ranging from 1 to 10 percent of that of Earth (Pollack and Yung, 1980). Measurements of  $N^{15}$  enrichment relative to  $N^{14}$  have been interpreted (e.g., McElroy et al., 1977) to suggest upper limits on the total atmospheric content at any time of about 200 millibars.

No matter which estimate of outgassing is used, it appears that the bulk of the volatiles outgassed by the planet is not in the atmosphere. Fanale and co-workers argue persuasively that most of these volatiles are stored in various forms in regolith and not in the polar caps (e.g., Fanale, 1976; Fanale and Cannon, 1979). For



*A Pioneer view of Venus' cloudy atmosphere.*

example, water exists as ground ice, as adsorbed water, and as chemically bound water. Thus, one expects that atmosphere-regolith interactions have been complex on Mars, yet this complexity must be understood if we are to unravel the past history of Mars' environment. We must understand how the various volatiles are stored in the regolith and how they can be cycled in and out, and on what time scales.

Viking Lander analyses and remote sensing from Earth strongly suggest that water is chemically bound in martian regolith materials. The relatively high water contents (1 to 1.9 percent) measured by the Viking GCMS\* are unlikely to be attributable entirely to water

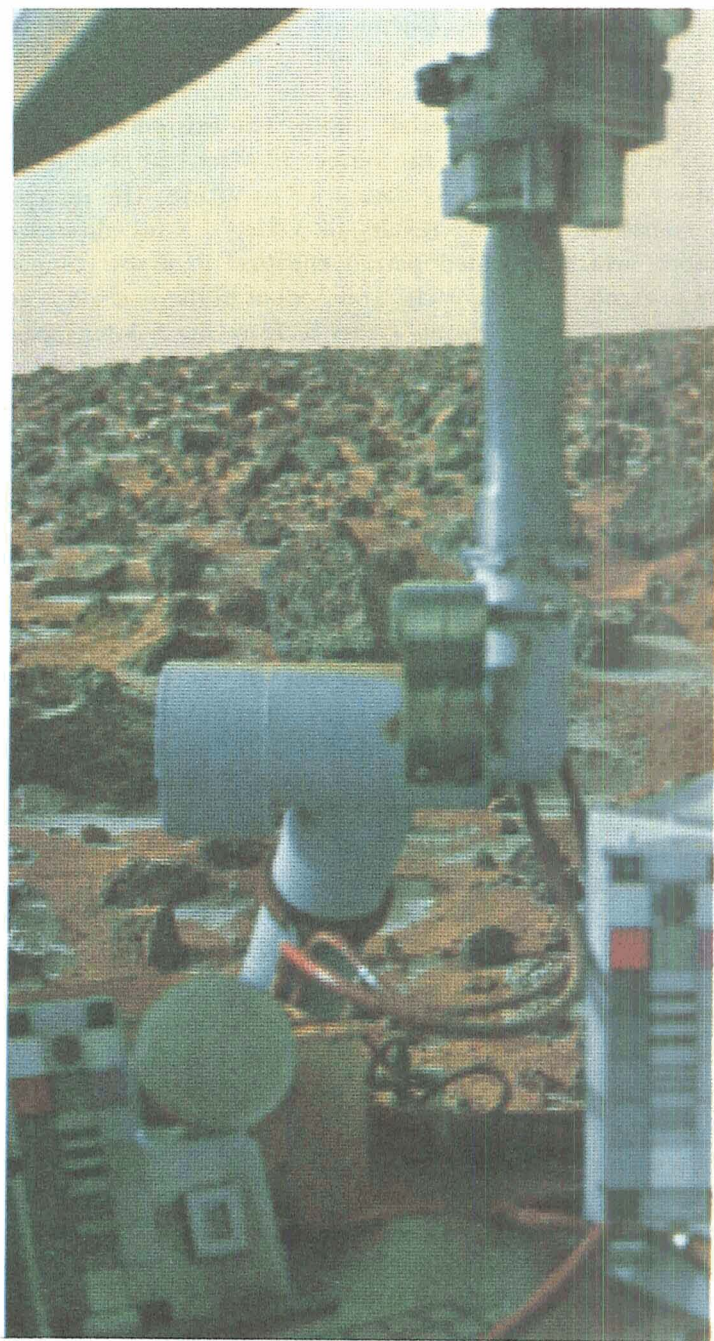
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\*Gas chromatograph mass spectrometer.

adsorbed on free surfaces. Chemically bound water or interlayer water in clays must be involved, as well as possibly water in hydrated salts that appear to be present in the "duricrusts" sampled by Viking (Clark, 1978; Gibson et al., 1980). The existence of hydrated minerals, including clays, on the surface of Mars had been revealed by a variety of remote sensing data prior to Viking. The interpretation is consistent with the results of Viking's X-ray fluorescence experiment, which provided partial chemical analyses compatible with the presence of a major clay component in the martian regolith (Clark, 1978). There is strong evidence from the Viking measurements that other volatiles, most notably sulfur, are stored chemically in the regolith. Although more CO<sub>2</sub> is stored in the regolith than is present in the atmosphere or in the polar caps, at most a minor amount is in the form of carbonates (Fanale and Cannon, 1979). The Viking GCMS observed a CO<sub>2</sub> release pattern in heated Mars soils that is said to be matched better by the desorption of CO<sub>2</sub> from clays than by release from thermal-labile carbonates.

Clearly, the regolith of Mars is chemically extremely complex. The weathering processes in it are very poorly understood, even under current environmental conditions. If at some past epoch liquid water existed in the surface layer, then the chemical incorporation of water, CO<sub>2</sub>, and other volatiles into the regolith would be relatively easy to understand. In the absence of liquid water, one might have to rely on ultraviolet-simulated chemical weathering, a process about which considerable debate remains. Fortunately, ultraviolet-simulated vapor-solid weathering is not the only plausible mechanism for fixing volatiles into the regolith of Mars. When lavas flow over, or intrusions are emplaced into, hard frozen soil on Earth, extensive interaction between preexisting soil, igneous rock, and remobilized volatiles occurs. Such interaction sometimes produces a volatile-rich melange soil called palagonite. Conditions on Mars seem favorable for similar processes, and terrestrial palagonites have optical properties quite similar to those of martian soils.

Thus, a first-order problem in the geologic study of Mars is to understand the current weathering processes and the nature, extent, and accessibility of various volatile reservoirs. Such an understanding is essential if we are to trace the likely history of the martian atmosphere. Only with such a history in hand can we determine the effectiveness of various regolith and surface processes throughout the age of the planet. The fundamental problem of understanding



*Frost on Mars.*



weathering and regolith-atmosphere interactions under present conditions can be tackled by thorough laboratory investigations. Special attention should be paid to detailed studies of analog terrestrial soils (e.g., from the Dry Valleys of Antarctica) and to terrestrial palagonites.

#### **4.5. Summary**

In a fundamental sense planetary geology relies on the progress of geochemical studies for the framework of its investigations. Developments that improve our knowledge of the processes in the early solar system provide firmer initial conditions for studying the geologic evolutions of planets—initial bulk compositions, volatile content, radioactive content, which is closely related to internal heating and degree of outgassing, etc. Absolute chronologies, which can only be obtained by geochemical studies of isotopes, are also essential for our studies. In the broadest sense, the fundamental task of geochemistry—the analysis of planetary samples—provides essential constraints on the nature and timing of events that affected the sampled bodies.

In the inner solar system there are important fundamental problems associated with the evolutions of the atmospheres of the Earthlike planets that can only be addressed through geochemical techniques. A key question in this context remains the initial distribution of rare gases in the materials that accreted at various distances from the Sun and its connection to the total volatile content. It has become the practice to infer the total volatile content and outgassing histories of terrestrial planets from measurements of rare gas abundances. The assumptions implicit in such techniques must be thoroughly understood and their validity ascertained. Obviously, in terms of surface geology it does make a significant difference whether or not Venus outgassed the equivalent of an ocean of water, or whether or not the atmospheric pressure on Mars has always been close to its current low value.

Many geologic processes involve the transport of weathering products. Thus, the rates and processes of past and present weathering are of key importance. For planets with atmospheres this problem is complicated by chemistry. The weathering processes (both past and present) on Mars and Venus must be thoroughly investigated. Relevant laboratory studies and, in the case of Mars, appropriate analog studies, should be pursued vigorously.



We also need a better understanding of the processes involved in the development of regoliths in general, especially on icy bodies, and on objects such as Amalthea and Europa, and perhaps even Iapetus, which may be subject to significant fluxes of foreign contaminating material.

The most effective strategy for the study of a planet's surface processes and composition is to proceed systematically with the mineralogic, petrologic, and chemical characterizations of its components. However, it is insufficient merely to analyze chemically the surface rocks, soils, or atmospheres; some assessment must be made of the geologic history of the samples. Determination of the mineralogy, texture, lithology, and other properties of the rock that might be relevant to origin is required. Mineralogic composition is particularly important in this context, since mineral assemblages reflect both major element chemistry and conditions of formation; it is therefore far more diagnostic of rock types and formative processes than chemical composition alone. Indeed, if a choice must be made between a mineralogic and a chemical analysis, most geologists would opt for the mineralogic analysis because it provides much more than just chemical information. For example, the X-ray analysis of the martian surface soils obtained by the Viking Landers is incomplete because we do not know what mineral components and alteration products made up the samples analyzed.

Future exploration strategy for the planets, satellites, and asteroids should be more comprehensive than that carried out for the Moon in the past. In the case of the Moon, difficult experiments were deferred until samples were available for analysis on Earth. Because the acquisition of samples from other bodies will be far more costly and technologically difficult, selected detailed investigations should precede sample return. On Mars, for example, experiments such as age determinations, petrologic characterization, and isotopic and trace element studies need not be delayed until samples are returned to Earth. Instruments necessary for performing such measurements remotely should be developed and tested.

The success of any geochemical exploration program will depend largely on how sampling sites are chosen. Information from geochemical orbiters and mappers, along with Earth-based instruments, are crucial in selecting sites for detailed study. The usefulness of most remote sensing techniques depends not so much on the precision with which they can determine surface chemistry, but

on their ability to detect differences. Careful preparatory study is required to determine the variability of surface materials, the areal extent of geologic units, as well as their likely modes of origin. The maximum scientific return from the investigation of any extraterrestrial sample will be realized only if the detailed geologic context of the sample is established.



## **5 Geophysics in the Planetary Geology Context**

Geophysical observations of planets consist of measurements of such quantities as gravity, topography, magnetic fields, heat flow, and seismic wave velocities. These data must then be interpreted in terms of physical models to derive information on the planet's thermal history, internal state, surface rheology, etc. Often geological and geophysical techniques are used in concert to suggest or constrain models. For example, photogeologic mapping and relative dating of features can be used together with gravity and topographic data in studies of tectonics. In this report we discuss planetary geophysics only in the most general terms, paying specific attention to the important interplay between this discipline and planetary geology.

### **5.1. Geological Constraints on Thermal Histories**

Historically, moment of inertia and mean density measurements were among the first data to become available for the terrestrial planets. These measurements, coupled with photogeologic information on the nature of the planets' surfaces, and with models for planetary accretion, made it possible to construct early models of the internal structure and thermal histories of the terrestrial planets (Hsui and Toksoz, 1977; Johnston and Toksoz, 1977; Toksoz et al., 1978; Buck and Toksoz, 1980). In the absence of seismic and heat flow data (except for the Moon), these first models were not well constrained, and clues to additional boundary conditions were sought from the records preserved on the surfaces of these objects.

Faulting and volcanism on a planetary surface can be closely related to the thermal evolution of the planet (Head and Solomon, 1981). Interior warming leads to global expansion, surface extensional tectonics, and a crustal stress system that aids the extrusion of volcanic products. On the other hand, interior cooling leads to contraction, compressional tectonics, and crustal stresses that act to shut off surface volcanism. This relationship between thermal history and the global tectonic history of the Moon, Mercury, and Mars has been explored extensively (Solomon and Chaiken, 1976; Solomon, 1977, 1978). Time-dependent global stress fields have also been used in combination with lithospheric flexure theory to explain the spatial and temporal relationships of linear rilles and ridges around lunar mare basins (Solomon and Head, 1979, 1980; Comer et al., 1979). A similar technique was used by Thurber and Toksoz (1978) to estimate the thickness of the elastic lithosphere in the Tharsis region of Mars.

## **5.2. Gravity and Topography Data**

At present, gravity and topography provide virtually our only direct information on the state of the interior of the terrestrial planets (except in the cases of Earth and the Moon). In general, the height of topography places an upper bound on the finite strength of the lithosphere, as does the gravity load where it can be directly correlated to crustal features. If only broad resolution data are available, the correlation between the gravity and topography power spectra may be used to provide information of the global degree of compensation (be it static or dynamic) and can indicate whether significant lateral density inhomogeneities are present at depth within the planet.

Thurber and Solomon (1978) used a set of crustal models to examine the degree of lunar isostasy, the probable mode of compensation, and the thickness of the basalt fill in mare basins. Lambek (1979) used power spectra of martian topography and gravity to show that long wavelength density anomalies on the planet are concentrated in a relatively thick lithosphere, in contrast to Earth, where such anomalies originate in the deep mantle. He also found that the lithospheric thickness implied over most of the planet was consistent with predictions of existing thermal models, but that the wavelengths associated with the Tharsis plateau demanded either a much colder interior or some form of dynamic support. Phillips et

al. (1981) used similar techniques to analyze the support of the Aphrodite Terra region of Venus. They concluded that this feature was either quite young (less than  $10^7$  years) or was dynamically supported by convection. Either alternative implies a thermally active planet.

If reasonably high resolution data are available, as is the case for Mars, more detailed global modeling can be performed using observed surface tectonic features as an additional constraint. Banerdt et al. (1982) computed global stress fields for Mars using the observed gravity and topography as boundary conditions. The results of their more detailed computations agreed closely with Lambek's (1979) conclusions. In addition, they found evidence of two distinct episodes in Tharsis' history, one of thermally driven construction, followed by a gradual loss of support and collapse. They also concluded that partial thermal support must exist at present. Given sufficient gravity and altimetry data, along with high-resolution radar imaging of the surface, the same types of analysis could profitably be performed for Venus.

In addition to the global information provided by the long wavelength topography and gravity data, much can be learned by studying the signatures of smaller features. This type of analysis has been carried out for many features on the Moon (Dvorak and Phillips, 1979; Dvorak, 1979). Such studies indicate that the outer portions of the Moon are thick, cold, and rigid. Preliminary work has also been done on Mars (Sjogren, 1979; Sjogren and Wimberly, 1981) and Venus (Phillips et al., 1979; Sjogren et al., 1980; Cazenave and Dominh, 1981) and has yielded information on lithosphere strength and viscosity, crustal thickness, and mode of compensation. One drawback, however, has been that local topography data have been very limited. High-resolution topographic maps are now available for several important surface loads, including the Tharsis volcanoes on Mars, and accurate estimates of the lithosphere thickness can be made from the shape of the surface flexure and the gravity signature (Solomon and Head, 1982). In the past, such estimates were made without the topographic data by substituting observations of concentric fracturing around loads, a procedure involving much greater uncertainties in interpretation.

There are many features on the solid planets in the solar system that await to be analyzed in detail. Lunar farside basins, for example, could be studied to compare the farside crust with that of

the near side. Investigation of volcanic piles both on and off Tharsis could give estimates of lithospheric and crustal thicknesses at various places on Mars. The Caloris basin could be used to derive the crustal structure of Mercury. A host of landforms on Venus could be used to further our understanding of that planet's interior.

Loading of the lithosphere by the accumulation of volcanic material, or any mountain-building process, may lead to overall stress distributions that require compensation. If the history of such surface loads can be constrained independently by relative age dating, then estimates of the mantle viscosity and/or "paleoviscosity" may be made. If the effective viscosity is much larger than that of Earth's mantle, then the load response time is long with respect to the age of the planet and the "load" may be supported by the mechanical strength of the interior. Studies of lunar floor-fractured craters (Hall et al., 1981) and lunar impact basins (Solomon et al., 1982) have provided evidence for viscous relaxation of lunar topography, and suggest that differences in crustal viscosity exist over a planet's surface; these differences probably indicate variations in crustal temperature profiles. From the lateral extent (or spherical harmonic degree) and magnitude of the topographic and gravity anomaly supported, constraints on the thickness of a mechanical lithosphere can be derived. If the wavelengths of lithospheric flexure are relatively large, then the lithosphere may be assumed to be very rigid and probably very thick. One alternative to support by finite strength in thick lithospheres is that density anomalies occur due to deep ( $>500$  km) convective circulation driven by thermal and/or chemical density imbalances that require times longer than 4.5 billion years to be dissipated. However, patterns and rates of convective circulation in deep planetary mantles may be more closely correlated with the rates and regional extent of planetary outgassing and volcanism than with regional density and topographic anomalies.

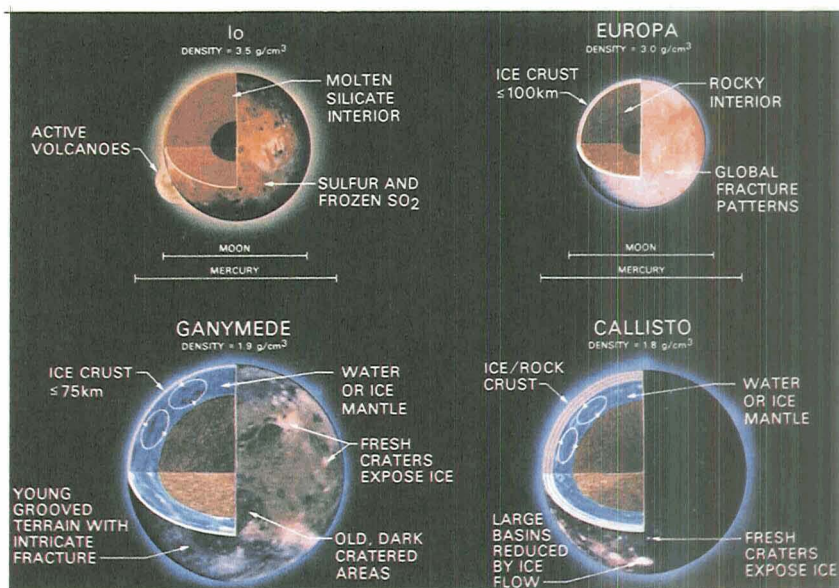
### **5.3. Shapes of Planets and Satellites**

For Earth and the Moon, seismic information enables us to construct detailed models of the interiors that describe both the internal density distributions and the possible locations of solid-liquid interfaces. For other planets and satellites, this method is not available, and our information on the nature of the interiors, apart from a few clues from electromagnetic sounding (Hide, 1978),

comes from determinations of the mean density and measurements of the departure of the mean global shape from perfect sphericity.

Rotational and, in the case of the satellites, tidal forces distort bodies to a degree determined by the internal density distribution and by the strength, or state of relaxation, of the solid parts. The degree of distortion can be determined either by measurements of the gravitational moments ( $J_2$ ,  $J_4$ , etc.) or by a measurement of the mean global shape. Measurement of  $J_2$  or of the shape of a body in hydrostatic equilibrium gives information equivalent to a knowledge of the body's moment of inertia once the rotational period is known (Cook, 1973).

The shapes of some of the inner satellites of Jupiter and Saturn are of particular interest in this context. Lewis (1971) and Consolmagno and Lewis (1976, 1977) have argued that some, but not all, of these satellites could be differentiated and could possess deep mantles of water and water-ice and rocky silicate cores. Dermott (1979) has shown that a wide range of internal density distributions have an appreciable effect on the shapes and gravitational moments of some of these satellites.



*Schematic comparison of the physical characteristics of the Galilean satellites of Jupiter.*



Specifically, such calculations suggest that if the shape factor,  $A-C$  (the difference of the longest and shortest axes of the triaxial ellipsoidal figure), can be measured to a precision of 1 or 2 km, then we will be able to determine whether the satellites Io, Mimas, Enceladus, and Tethys are differentiated and estimate the sizes of the possible cores. The gravitational moment,  $G(B-A)$ , can, in the best circumstances, be measured to a precision  $\sim 10^6 \text{ km}^5 \text{ sec}^{-2}$  (Hubbard and Anderson, 1978), and it seems that such measurements could be useful in determining the degree of differentiation only in the case of Io and possibly Titan (Dermott, 1979). However, precise measurements of the shapes alone are capable of yielding information on the internal structures of Mimas, Enceladus, and Tethys and probably of other objects as well.

#### **5.4. Magnetic Fields**

Measurements of the external magnetic field also provide important clues as to whether or not convection is an efficient mechanism of heat transport in a planet's interior. For Earthlike planets strong magnetic fields indicate a molten state for a dense metallic core, and consequently a warm mantle. Since Earth has a strong magnetic field, it is clear that mantle convection is a relatively inefficient mechanism of heat removal. It is difficult to quantify how cool a planetary interior may become due to convection when a thick, immobile, nonsubducting lithosphere sits on top of the convecting layer. Accurate theoretical estimates of the interior temperature structure and evolution are crucial, however, for correlation with magnetic events, tectonic reconstructions, estimates of crustal chemical evolution, and lithospheric thickness. Recent convection calculations with temperature-dependent viscosity and spherical geometry show that the terrestrial planets equal to or larger in size than Mars may maintain both thick lithospheres and interiors hot enough to provide planetwide volcanism over geologic time.

#### **5.5. Outer Planet Satellites**

Most of our discussion so far has emphasized the terrestrial planets, but there is little doubt that much geophysical effort during the coming decade will go into the study of the satellites of Jupiter and Saturn. The same geophysical principles used for studying the terrestrial planets can be extended to these bodies. Thermal models

of the icy satellites have grown increasingly sophisticated, attempting to take into account solid-state convection and other factors (Parmentier and Head, 1979a,b; Thurber et al., 1980). Peale et al. (1979) used thermal models to predict volcanism due to tidal heating on Io; similar ideas are now being applied to explain the enigmatic surface of Enceladus. Research is also being done to explain the origin of tectonic features on the Galilean satellites, including domes on Ganymede (Squyres, 1980) and multiringed structures on Ganymede and Callisto (McKinnon and Melosh, 1980).

The list of geophysical questions concerning the outer planet satellites that need answering is already long and will certainly grow as we learn to understand these objects better. For example, we do not really know how important accretional energy was as a heat source in the evolution of the larger satellites. We do not even know whether most objects really are differentiated. Nor do we know whether any of the satellites can support large density anomalies in their interiors. We do not know how thick Io's lithosphere is, or whether the high topography on some parts of the satellite is compensated. In the case of Saturn's satellites, we do not know whether ammonia played a significant role in lowering melting temperatures in the interiors.

## **5.6. Summary**

Planetary geophysical observations traditionally include measurements of gravity, topography, and magnetic fields, as well as determinations of a planet's mass, mean radius, and density, and of its overall shape and figure. For Earth and the Moon, seismic and heat flow data are available and provide essential constraints on geophysical models. A major goal of planetary exploration should be to obtain similar data for other important solid bodies of our solar system.

Lacking seismic and heat flow data for most objects, information on gravity and topography, interpreted in the context of observed surface features, has been relied on to provide most of the constraints needed to develop models of how interior processes have affected the surface evolution of planets and satellites. Often, remote sensing techniques (photometry, spectrophotometry, and radar and thermal measurements) can provide valuable additional clues (chapter 8).

Although mass, radius, and mean density data are well established for the terrestrial planets, these essential parameters remain poorly determined for many important objects in the asteroid belt and beyond. As the Voyager experience with the satellites of Jupiter and Saturn demonstrates, accurate mean densities require extremely precise determinations not only of the masses, but of the radii as well (chapter 6). A byproduct of accurate radii determinations is a measurement of the body's shape, which often contains important information on internal structure.

## 6 Geodesy and Cartography

Geodesy and cartography of planets and their satellites are natural extensions of the same scientific disciplines that are used to describe the size and shape of Earth, define its coordinate system, develop control nets, measure gravity fields, and produce accurate, useful maps. The techniques for making planetary measurements are frequently very different from those used on Earth, and the accuracy is generally not as high. Yet the data—including basic parameters such as rotation rate and average radius and shape, as well as detailed global and regional maps showing the extent and relative locations of surface features and (in the best of cases) their vertical relief—are essential to all geologic and physical studies of planets and satellites.

### 6.1. Introduction

Geodesy and cartography involve the combination and portrayal of data from a large body of scientific investigation. For convenience, the required components can be divided into four interrelated topics:

1. A body-fixed, mass-centered coordinate system must be defined for the planet or satellite and related to an inertial astronomical coordinate system (such as the 1950.0 Earth equatorial coordinate system). For this purpose, a prime meridian must be defined once the rotation rate and the spin axis of the body have been determined.
2. The size and shape of the planet or satellite must be measured and a control network consisting of the coordinates of a large number of identifiable surface points established. This topic is generally referred to as geometric geodesy.

3. The mass and mass distribution must be determined, and the coefficients of the spherical harmonic expansions of the gravity potential derived. This topic is generally referred to as physical geodesy.
4. Surface features and other physical data must be depicted on planetwide, detailed maps for scientific, engineering, and navigation purposes.

In summary, for all the bodies of the solar system, we seek to determine the rotation rates, the directions of the rotation vectors, the sizes and shapes, and the masses and gravity fields. We also desire to establish the location and elevation of surface features and produce maps that portray these and related surface properties. The importance of lunar and planetary geodesy is discussed in *Geodesy: Trends and Prospects* (National Academy of Sciences, 1978), and the fundamental role of global maps in planetary research is stressed in *Strategy for Exploration of the Inner Planets: 1977-1987* (National Academy of Sciences, 1978).

Sources of data include Earth-based optical telescopes and radar, Earth orbital telescopes, and flyby, orbital, and landing spacecraft. The accuracy with which various parameters can be determined varies greatly with the type of mission to a particular planet or satellite and, of course, with the number of such missions and with the instrumentation each carries. Orbiters and landers have investigated the Moon and Mars, so data for these two bodies are the most accurate. Flyby missions have flown past the Moon, Mars, Mercury, and the satellites of Jupiter and Saturn, obtaining essential gravity and imaging information. The Pioneer Venus Mission carried a radar altimeter that yielded elevation measurements of the topography and low-resolution imaging.

## **6.2. Available Data Base**

Both the United States and the Soviet Union have vigorous programs designed to explore the solar system and extensive cartographic efforts to exploit the abundant pictorial data from their missions.

Table 2 lists the missions and cameras that acquired the pictures fundamental to the cartographic planetary effort. Through photogrammetry these pictures were used to compute control networks over large areas and to compile map products. In producing a map, a cartographer studies most or all of the available pictures to

*Table 2.—Important Missions and Cameras That Acquired Pictures Used for Large Area Control and Mapping of Planets and Satellites*

| Mission name      | Mission type   | Target                           | Camera type          | Camera format (mm) | Camera focal length (mm) | Mean standard error of measurement (mm) |
|-------------------|----------------|----------------------------------|----------------------|--------------------|--------------------------|---|
| Lunar Orbiter     | Orbiter        | Moon                             | 70 mm film           | 55 x 65            | 80                       | 0.030                                   |
| Apollo 15, 16, 17 | Orbiter        | Moon                             | 127 mm film return   | 114 x 114          | 86                       | 0.005–0.020                             |
| Soviet Zond 6, 8  | Flyby          | Moon                             | 190 mm film return   | 130 x 180          | 400                      | 0.020                                   |
| Mariner 9         | Orbiter        | Mars                             | Vidicon              | 9.6 x 12.5         | 50                       | 0.020                                   |
| Viking 1, 2       | Orbiter        | Mars                             | Vidicon              | 12.5 x 14.0        | 475                      | 0.020                                   |
| Soviet Mars 4, 5  | Flyby, Orbiter | Mars                             | 25.4 mm film readout | 22.5 x 23          | 52                       | 0.020                                   |
| Mariner 10        | Flyby          | Mercury                          | Vidicon              | 9.6 x 12.35        | 1500                     | 0.025                                   |
| Voyager 1, 2      | Flyby          | Satellites of Jupiter and Saturn | Vidicon              | 11.14 x 11.14      | 1500                     | 0.020                                   |

understand and portray the structure and characteristics of the surface. For most bodies there exists a mixture of imaging data—high-resolution in some regions and low in others. Since resolution is very important to understanding the nature of the surface, there is always the desire to seek as high resolution as possible. On the other hand, for computing control networks and compiling maps, it is important to have overlapping contiguous coverage. Thus, in the tradeoff of resolution and coverage, cartographers vote for coverage first, resolution second.

For terrestrial applications, aerial photographs are commonly used in the production of maps (American Society of Photogrammetry, 1980). For this purpose, mapping or metric cameras are specially designed to have almost distortion-free optics. The only planetary missions that carried similar cameras were Apollo 15, 16, and 17 and the Soviet Zond 6 and 8; of course, the film from such cameras must be returned to Earth. Most missions to the distant planets carried television camera systems or photographic film with on-board processing and line-scan readout. The geometric distortions

inherent in these systems were calibrated and removed in the measurement of the pictures.

Measurements of the control point locations on the pictures are incorporated in an analytical triangulation that determines the planetary coordinates of the control points on the surface. In this application, the pictures cover a large region, or perhaps the entire surface, of a planet or satellite. The standard error of the residuals in the analytical triangulation provides an overall estimate of the accuracy of measurements of the control point locations, the ability to remove the camera's geometric distortions from the measurements, and the quality of other parameters incorporated in the computation. Typical values for the standard errors are given in the last column of Table 2.

For mapping purposes, large image formats are preferred to small ones; high resolution and contrast are important. In photogrammetric work, this requirement translates into large format and small standard error of measurement. Based on this criterion, the film-return camera systems (Apollo 15, 16, and 17 and Zond 6 and 8) are best, and the television camera systems flown on missions such as Mariner and Voyager are the poorest. The conventional aerial camera has a well-calibrated wide-angle lens and large format, whereas the typical planetary camera has a narrow-angle lens and a small format and usually is subject to large electronic distortions that are difficult to calibrate.

Some bodies of the solar system, such as the planet Venus and Saturn's satellite Titan, have dense cloudy atmospheres, making it impossible to image their surfaces with conventional cameras. These surfaces must be explored with radar. Earth-based radar (at Arecibo and Goldstone) and the radar altimeter on the Pioneer Venus mission produced limited but exciting cartographic data for Venus. However, the planetwide mapping of Venus will have to await data from future orbiting radar missions.

### **6.3. The Coordinate Systems of Planets and Satellites**

A working group on the cartographic coordinates and rotational elements of the planets and satellites was established at the International Astronomical Union (IAU) General Assembly at Grenoble in 1976. This working group reported to the IAU General Assembly in 1979 (Davies et al., 1980; Davies, 1982). A somewhat smaller group was established in 1979 with overlapping member-

ship with the 1976 group to make necessary changes anticipated in the light of the Voyager encounters with Jupiter and Saturn.

The group adopted the following guiding principles:

1. The rotational pole of a planet or satellite that lies on the north side of the invariable plane shall be called north, and northern latitudes shall be designated positive.
2. The planetographic longitude of the central meridian, as observed from a direction fixed with respect to an inertial coordinate system, shall increase with time. The range of longitudes shall extend from  $0^\circ$  to  $360^\circ$ .

As a result of principle 2, bodies with prograde rotation such as Mercury, Mars, and the satellites of Jupiter and Saturn have longitudes that increase from  $0^\circ$  to  $360^\circ$  from east to west. However, the retrograde rotation of Venus and of the satellites of Uranus result in longitudes that increase from  $0^\circ$  to  $360^\circ$  from west to east. Exceptions to Principle 2 are the Moon and Earth, where longitudes from  $0^\circ$  to  $180^\circ$  are measured east and west of a prime meridian.

The cartographic coordinate system is defined by reference to the planet's or satellite's axis of rotation and an arbitrarily selected prime meridian. In most cases, a clearly defined surface feature (usually a small crater) is assigned a specific longitude: Hun Kal defines  $20^\circ$  on Mercury, Airy-0 defines  $0^\circ$  on Mars, Cilix defines  $182^\circ$  on Europa, Anat defines  $128^\circ$  on Ganymede, and Saga defines  $326^\circ$  on Callisto. Since it was not obvious how to choose a small *permanent* feature on Io because of the extensive volcanism, the astronomical definition is used—the prime meridian is the sub-Jupiter longitude at the first superior conjunction after 1950.0. The prime meridian of this moon passes through the mean sub-Earth direction.

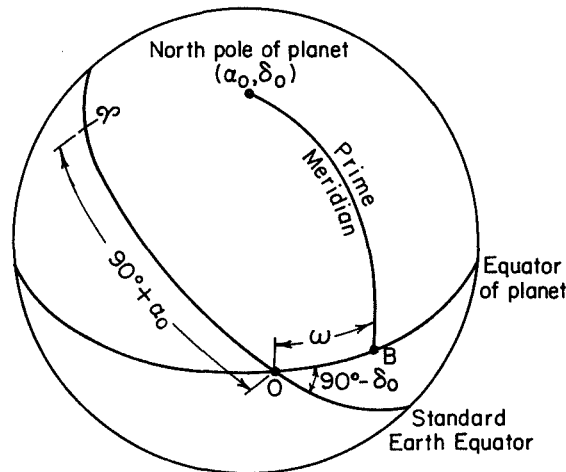
The rotational elements of the planets and satellites are derived relative to the standard celestial equator and equinox of the 1950.0 inertial coordinate system, and time is measured in ephemeris days or Julian ephemeris centuries of 36 525 days from the standard epoch of 1950 January 1.0 ET (or JED 2 433 282.5). The direction of the north pole is specified by its right ascension,  $\alpha_0$ , and declination,  $\delta_0$ . The prime meridian is specified by the angle,  $\omega$ , measured along the planet's equator on the standard equator to the point, B, where the prime meridian crosses the planet's equator (see figure



below). If  $\omega$  increases with time, the planet has direct rotation; if  $\omega$  decreases, the rotation is retrograde.

For the planets, expressions for  $\alpha_0$ ,  $\delta_0$ , and  $\omega$  are relatively simple, since precession periods are long, and mutual gravitational perturbations are small. On the other hand, the corresponding expressions for the satellites are frequently complex, as the theory of their motions contains many terms. Expressions for  $\alpha_0$ ,  $\delta_0$ , and  $\omega$  for planets and satellites for which maps are currently being made are summarized by Davies (1982).

Table 3 contains the updated parameters for the reference spheroids for those planets and satellites in the current cartography program.



*Definition of the prime meridian of a planet or satellite.*

#### 6.4. Geometric Geodesy

Coordinates of features observed on images of planets and satellites are computed photogrammetrically using essentially the same techniques that have been developed to compute the coordinates of features on Earth from aerial photography. Usually image formats are small and the measurement errors relatively large (see Table 2) when compared to results obtained from conventional aerial photography of Earth. Frequently the horizontal and vertical control nets are determined separately; the horizontal net is com-

*Table 3.—Recommended Reference Spheroids for the Planets and Satellites in the Cartography Program*

| Planet or satellite | Equatorial<br>radius<br>(km) | Polar<br>flattening |
|---------------------|------------------------------|---------------------|
| Mercury .....       | 2439                         | 0                   |
| Venus .....         | 6051                         | 0                   |
| Moon .....          | 1738                         | 0                   |
| Mars .....          | 3393.4                       | 0.005               |
| Europa .....        | 1569                         | 0                   |
| Ganymede .....      | 2631                         | 0                   |
| Callisto .....      | 2400                         | 0                   |
| Mimas .....         | 196                          | 0                   |
| Enceladus .....     | 250                          | 0                   |
| Tethys .....        | 525                          | 0                   |
| Dione .....         | 560                          | 0                   |
| Rhea .....          | 765                          | 0                   |
| Iapetus .....       | 725                          | 0                   |

puted by analytical triangulation, and the vertical controlled by auxiliary measurements and analysis.

Nonphotogrammetric data have been crucial to the development of both horizontal and vertical control nets on some objects. Analysis of laser ranging of lunar retroreflectors and differential very-long-baseline interferometry using ALSEP\* transmitters has revolutionized the study of lunar dynamics and provided extremely accurate coordinates for a few points on the lunar surface (Bender et al., 1973; Ferrari et al., 1980). Analysis of radio tracking data from both Viking Landers has led to very accurate values for the direction of Mars' rotation axis, rotation rate, and the coordinates of the two lander sites (Mayo et al., 1977; Michael, 1979).

The Moon is the only extraterrestrial body for which telescopic photographic plates have made a significant contribution to the establishment of a control net. Telescopic data are still important and in use (Meyer, 1980) because spacecraft have not yet produced better materials for this purpose over large regions of the near side.

\*Apollo lunar surface experiments package.

There is no single unified control net for the Moon; control consists of patching a series of regional blocks (Table 4). Vertical control is computed photogrammetrically in the telescopic, Apollo, and Zond nets; the Apollo laser altimeter is another source of very useful vertical data. The coordinates of the lunar retroreflectors and the ALSEP transmitters have been accurately determined (Bender et al., 1973; Ferrari et al., 1980). Moreover, the Apollo 15 retroreflector and the Apollo 16 and 17 transmitters have been located on the panoramic pictures and their locations transferred to the mapping pictures (Schirmerman, 1976), so these coordinates can be used directly to constrain the Apollo control nets.

The horizontal control net of Mercury was computed photogrammetrically from pictures taken by the Mariner 10 spacecraft on its three encounters with Mercury (Davies and Katayama, 1976). All the control points were constrained to lie on a sphere with a radius

*Table 4.—Control Nets of Planets and Satellites Based on Pictures Taken by Spacecraft*

| Planet or satellite | Spacecraft           | Num-<br>ber of<br>points | Num-<br>ber of<br>pictures | Reference                         |
|---------------------|----------------------|--------------------------|----------------------------|-----------------------------------|
| Moon                | Lunar Orbiter        | 4900                     | 41                         | Positional Ref. System—<br>(1974) |
|                     | Apollo 15            |                          |                            | Schirmerman et al. (1973)         |
|                     | Apollo 15,<br>16, 17 |                          |                            | Schirmerman (1976)                |
|                     | Apollo 15,<br>16, 17 | 5324                     | 1244                       | Doyle et al. (1976)               |
|                     | Zond 6, 8            | 387                      |                            | Bolijshakov et al. (1975)         |
| Mars                | Zond 6, 8            | 131                      | 4                          | Ziman et al. (1975)               |
|                     | Mariner 9            | 4138                     | 1213                       | Davies et al. (1978)              |
|                     | Viking 1, 2          |                          |                            | Davis and Katayama (1983)         |
|                     | Mars 4, 5            | 200                      |                            | Tjuflin et al. (1980)             |
| Mercury             | Mariner 10           | 2378                     | 788                        | Davies and Katayama (1976)        |
| Io                  | Voyager 1, 2         | 504                      | 234                        | Davies and Katayama (1980)        |
| Europa              | Voyager 1, 2         | 112                      | 115                        | Davies and Katayama (1980)        |
| Ganymede            | Voyager 1, 2         | 1547                     | 282                        | Davies and Katayama (1980)        |
| Callisto            | Voyager 1, 2         | 439                      | 200                        | Davies and Katayama (1980)        |

of 2439 km. This radius is consistent with two occultation measurements made when the Mariner 10 spacecraft passed behind Mercury (Howard et al., 1974) and the measurements made from ground-based radar (Ash et al., 1971).

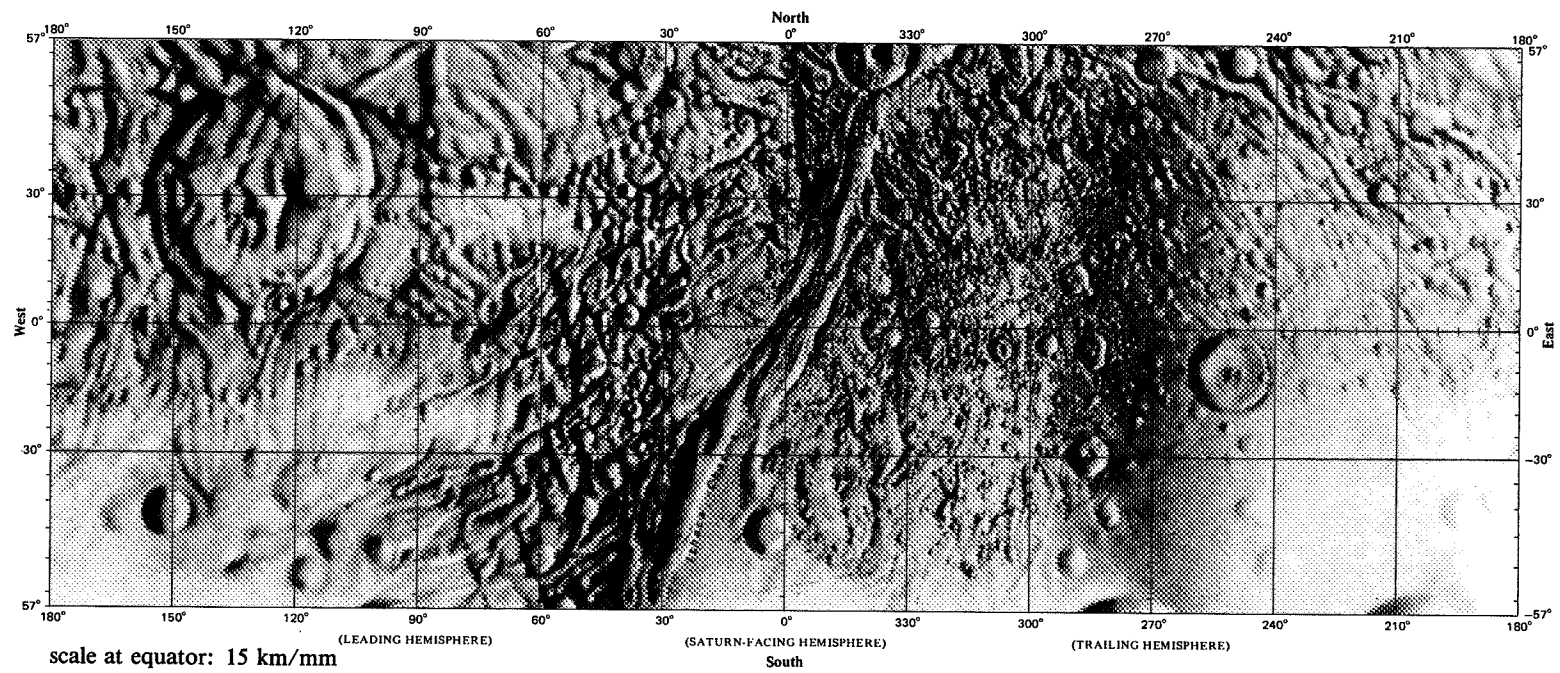
The computation of the planetwide horizontal control net of Venus will have to await data from a future Venus orbiting radar mission. However, the radar altimeter on the Venus Pioneer mission provided very good elevation data, so that for the first time the vertical control on a planet is more refined than the horizontal control.

The Mariner 9 spacecraft acquired pictures of most of the surface of Mars at approximately 1 to 2 km resolution, making it possible for the first time to compute a planetwide horizontal control net from a single source. Later, data from Viking Orbiter 1 and 2 pictures were included (Davies et al., 1978). The location of the Viking 1 Lander on the surface of Mars was identified on high-resolution Viking Orbiter pictures (Morris and Jones, 1980), and accurate coordinates of the Lander site (Michael, 1979) were incorporated into the analytical triangulation. Vertical control on Mars has been derived from many sources (Wu, 1978); these include Mariner 9 and Viking 1 and 2 radio occultations, ground-based radar observations using the Haystack and Goldstone antennas, and measurements by the Mariner 9 ultraviolet spectrometer, infrared interferometer spectrometer.

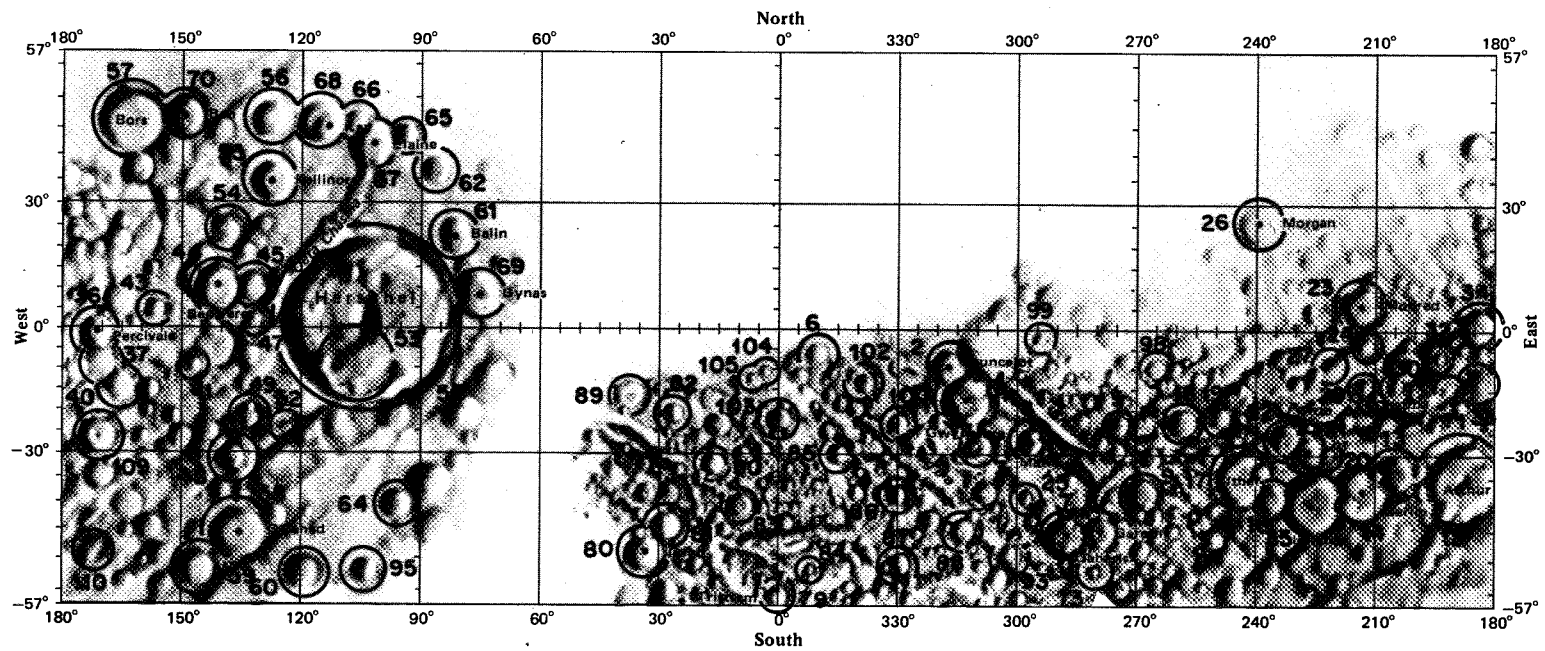
The Voyager 1 and 2 encounters with Jupiter provided numerous images of the Galilean satellites Io, Europa, Ganymede, and Callisto. Measurements of points on these pictures are being used to establish horizontal control nets and calculate mean radii (Davies and Katayama, 1980). Because these were flyby missions, the resolution varies greatly with longitude on these bodies.

The Voyager 1 encounter with Saturn produced images of the satellites Mimas, Tethys, Dione, and Rhea with good resolution over some regions. Measurements of points in these pictures are being made and horizontal control nets computed. So far radii have been determined only by limb measurements (Table 3).

As the exploration of the solar system proceeds, work on the control nets will continue as new data become available.



*Shaded relief map of Saturn's satellite Tethys based on Voyager images.*



*Preliminary shaded relief map of Saturn's satellite Mimas, showing the locations of control points.*

## 6.5. Physical Geodesy

Research on the gravity fields of planets and satellites has progressed rapidly and has been recognized as an essential aspect of solar system exploration in *Geodesy: Trends and Prospects and Strategy for Exploration of the Inner Planets: 1977-1987* (National Academy of Sciences, 1978). A large number of measurements must be made to characterize the gravity field, and, since the number of missions to any body is still relatively small, there are gaps in the desired data. However, significant progress has been made in the cases of the Moon, Venus, and Mars.

The first parameter of the gravity field to measure is the mass, which can be determined either from Doppler tracking of a flyby spacecraft or from the period of revolution of an orbiter. The gravity field of a planet or satellite is usually described in terms of its spherical harmonics (Cook, 1973). The values of the harmonic coefficients can be derived from observations of the motions of orbiting natural satellites; however, the preferred method is from analysis of Doppler tracking of an orbiting spacecraft. Data from both a low-altitude, high-inclination orbit and a high-altitude, low-inclination circular orbit are desirable. In practice, orbits are not optimum, and it is necessary to try to obtain the best possible results from available data. Table 5 gives values for the masses and  $J_2$  for planets and satellites in the cartographic program.

Values for the mass and  $J_2$  of Mercury were derived by Esposito et al. (1978) from the first and third Mariner 10 flybys. Because this was a flyby mission, it was not possible to obtain estimates of higher-order harmonic coefficients.

The mass of Venus was determined by analysis of Mariner 5 (Anderson and Efron, 1969) and Mariner 10 (Howard et al., 1974) tracking data acquired during their flybys. Analysis of 220 days of Doppler radio tracking data from the Pioneer Venus orbiter has given values for the sixth-degree and sixth-order harmonic coefficients of the gravity field (Ananda et al., 1980). As the mission continues, additional data should increase confidence in the results and perhaps permit solving for higher-order coefficients.

The lunar laser ranging experiment led to an improved lunar orbit determination and to accurate measurements of the physical librations (Bender et al., 1973). Doppler tracking data from Apollo 15 and 16 subsatellites and Lunar Orbiter 5 have been combined to

Table 5.—Values of the Masses and  $J_2$  for the Planets and Satellites in the Cartography Program

| Planet or satellite | Mass (g)               | $J_2$    |
|---------------------|------------------------|----------|
| Mercury.....        | $3.302 \times 10^{26}$ | 0.00008  |
| Venus.....          | $4.869 \times 10^{27}$ | 0.000006 |
| Moon.....           | $7.348 \times 10^{25}$ | 0.000202 |
| Mars.....           | $6.419 \times 10^{26}$ | 0.001959 |
| Io.....             | $8.926 \times 10^{25}$ | 0.0022   |
| Europa.....         | $4.862 \times 10^{25}$ | 0.00054  |
| Ganymede.....       | $1.489 \times 10^{26}$ | 0.00023  |
| Callisto.....       | $1.064 \times 10^{26}$ | 0.000053 |
| Mimas.....          | $3.76 \times 10^{22}$  | 0.015    |
| Enceladus.....      | $7.40 \times 10^{22}$  | 0.0097   |
| Tethys.....         | $6.26 \times 10^{23}$  | 0.0055   |
| Dione.....          | $1.05 \times 10^{24}$  | 0.0021   |
| Rhea.....           | $2.28 \times 10^{24}$  | 0.0014   |

solve for a sixteenth-degree and sixteenth-order gravity model (Ferrari, 1977) and even one of the twentieth degree and twentieth order (Ananda, 1977). A new solution for low-order harmonic coefficients has been obtained by combining laser ranging data from the retroreflectors with Doppler tracking of Lunar Orbiter 4 and simultaneously solving for the lunar orbital elements, libration parameters, and seventh-degree and seventh-order harmonic coefficients (Ferrari et al., 1980).

The best measurement of the mass of Mars was derived from Mariner 4 data (Null, 1969). Studies of the gravity field of Mars were based on tracking data from the Mariner 9 spacecraft. For example, Sjogren et al. (1975) and Jordan and Lorell (1975) derived fourth-degree and fourth-order harmonic coefficients for the planet. Doppler tracking data from the two Viking orbiting spacecraft were combined with the Mariner 9 data to improve the understanding of the gravity field of Mars by Gapcynski et al. (1977) who derived sixth-degree and sixth-order harmonic coefficients, and by Christensen and Balmino (1979) who developed a twelfth-degree and twelfth-order gravity model.

The masses of the satellites of Jupiter and Saturn have been derived from observations of perturbations of their orbits. Recent



Voyager tracking data will improve some of these values. The values of  $J_2$  listed for the satellites in Table 5 were obtained by Dermott (1979), assuming that the bodies are in hydrostatic equilibrium. These satellites are all in synchronous rotation, and those close to their primary bodies are elongated in the planet's direction by tides. This factor accounts partly for the large values of  $J_2$  for Io, Mimas, Enceladus, and Tethys.

### 6.6. Cartography

Maps of the Moon have been prepared by astronomers since the time of Galileo. Shortly after the first spacecraft flew by the Moon, a program to produce lunar maps was started at the Aeronautical Chart and Information Center (ACIC), St. Louis, Missouri (Kopal and Carder, 1974). In modern terrestrial mapping, landforms are delineated by highly detailed contour lines, along with symbolic portrayal of cultural and hydrographic features. In the absence of cultural and hydrographic features on the Moon, accurate landform delineation is vital, yet data for contour compilation are extremely limited. Special airbrush techniques were therefore developed by skilled artists to portray the relief seen in pictures (Inge and Bridges, 1976; Batson, 1978). With practice and experience, the artists perfected their techniques and became expert photointerpreters as they studied pictures from many sources—telescopic photographic film, spacecraft photographic film, and spacecraft television images. Currently all lunar and planetary maps are produced at the U.S. Geological Survey in Flagstaff, Arizona. Some map series use mosaics to illustrate the topography, although mosaics are not as attractive as the artists' shaded relief painting and contain less information.

The problem of representing a spherical surface on a flat map has led to the development of a large variety of map projections. In the planetary program, conformal projections are popular because craters are common topographic features, and most of us like to see round craters round. In planetwide mapping series, Mercator projection sheets are usually used in the equatorial band, Lambert conformal projection sheets in the midlatitudes, and stereographic projection in the polar regions. Special-purpose large-scale maps are made on the above projections and occasionally on orthographic or transverse Mercator projections.

Computers generate and maintain data bases for map compilation. Using geometric parameters from the control net analytical

triangulation or from the Supplementary Experimenter Data Record (SEDR), the television pictures can be geometrically formatted into any one of the common projections for mosaics. The making of the mosaic can be carried out in the computer or by hand.

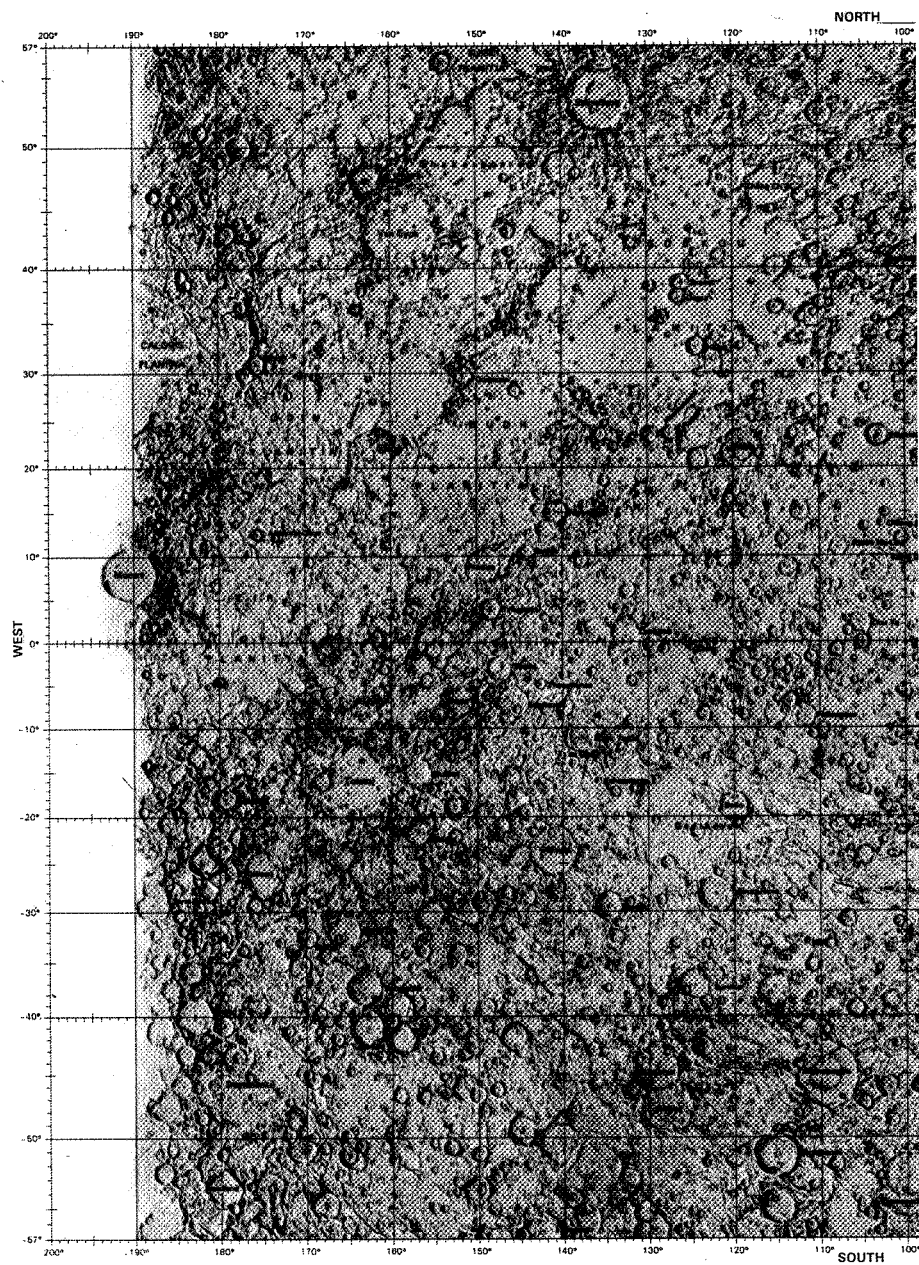
The reference surfaces of the planets and satellites in the cartographic program are given in Table 3. All are taken to be spheres except Mars, for which a spheroid is assumed (de Vaucouleurs et al., 1973). Contour lines have been added to some of the maps, indicating topographic elevations with respect to a defined datum. The datum for Venus and the Moon is a sphere, whereas the datum for Mars is defined by the fourth-degree and fourth-order spherical harmonic gravity field, with the zero altitude defined by the 6.105 mbar atmospheric pressure surface at a temperature of 273.01 K (Wu, 1978). This pressure and temperature correspond to the triple point of water.

The planetary mapping program has produced global maps, planetwide mapping series, and special-purpose maps, as well as globes and atlases (Batson, 1981). The global maps and mapping series, summarized in Table 6, include shaded relief, albedo, and topographic maps, mosaics, orthophotomaps, and color mosaics. Most of them have been digitized and are available in computer-compatible format.

A large number of special maps have been produced. Many special maps of the Moon were made to support the Apollo Landing site selection and the Apollo Lander operations. On Mars, special maps were produced to aid in the Viking Lander site selection process. Many special maps have been generated in support of particular planetary geology studies. Usually the special maps are at larger scale than is available in a planetwide series.

The International Astronomical Union (IAU) has established an organization responsible for the naming of features discovered on planets and satellites. The IAU Working Group for Planetary System Nomenclature was organized in 1973, with individual task groups for the Moon, Mercury, Venus, Mars, and Outer Solar System reporting to the working group. These task groups are responsible for the names that appear on the maps.

As indicated in *Strategy for Exploration of the Inner Planets: 1977-1987* (National Academy of Sciences, 1978), the global maps provide the fundamental framework for carrying many detailed investigations. Preliminary global maps are produced as soon as data become available. They are frequently used as a base for thematic



*Mercator map of Mercury.*

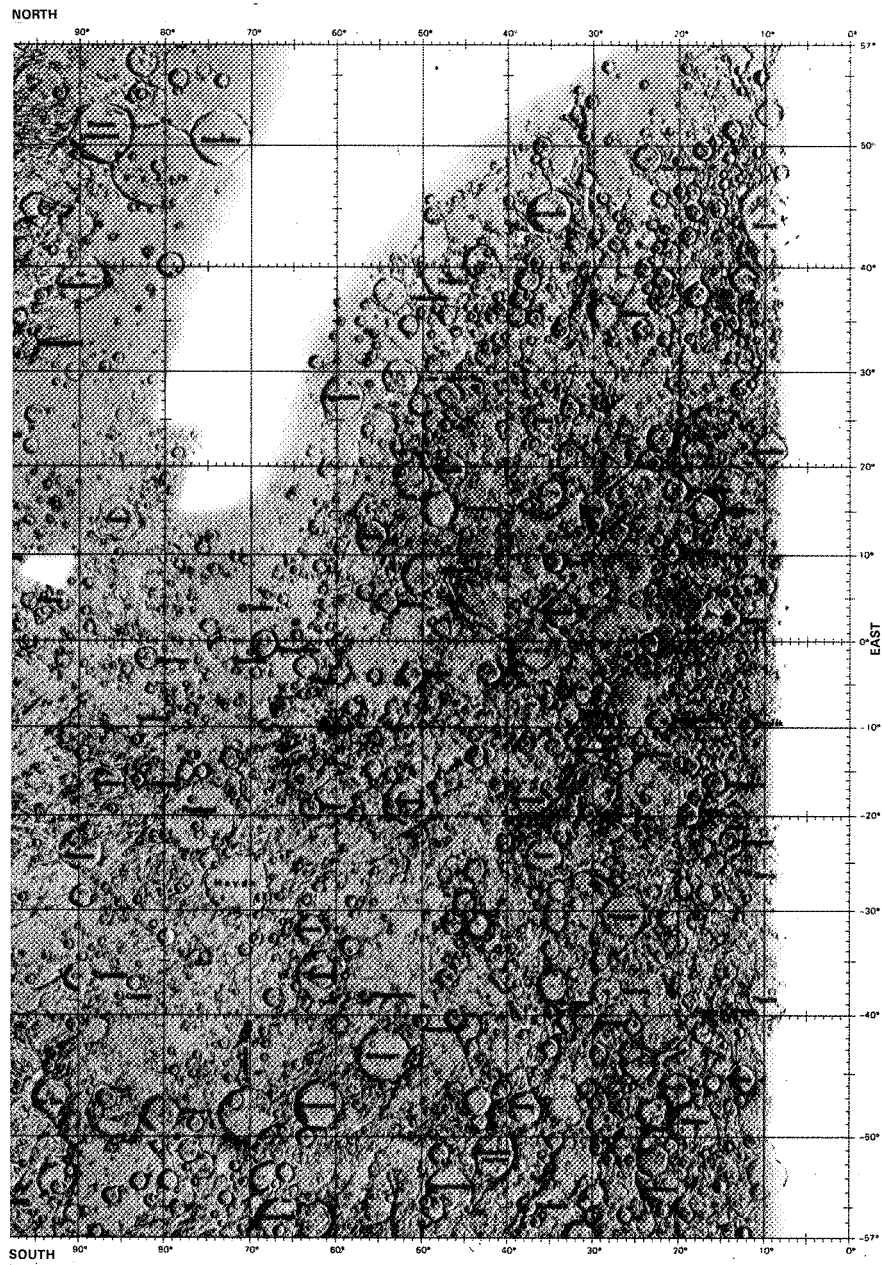


Table 6.—Global and Planetwide Mapping Series

| Planet or satellite | Scale                                  | Number of sheets  |
|---------------------|--|---|
| Mercury             | 1:25,000,000                           | 1   |
|                     | 1:15,000,000                           | 1   |
|                     | 1:5,000,000                            | 15 (5 Mercator, 8 Lambert, 2 stereographic projections)     |
| Venus               | 1:50,000,000 (topographic)             | 1   |
|                     | 1:5,000,000                            | 62 (24 Mercator, 36 Lambert, 2 stereographic projections)   |
| Moon                | 1:10,000,000                           | 1   |
|                     | 1:5,000,000                            | 3 (2 Mercator, 2 stereographic on one sheet projections)    |
|                     | 1:1,000,000 (topographic)              | 144 (36 Mercator, 108 Lambert, 2 stereographic projections) |
| Mars                | 1:250,000 (topographic, orthophotomap) | 576 (Transverse Mercator projection)                        |
|                     | 1:25,000,000                           | 1   |
|                     | 1:25,000,000 (topographic)             | 1   |
|                     | 1:15,000,000                           | 3   |
|                     | 1:5,000,000                            | 30 (16 Mercator, 12 Lambert, 2 stereographic projections)   |
|                     | 1:5,000,000 (topographic)              | 30  |
|                     | 1:2,000,000                            | 140 (64 Mercator, 56 Lambert, 20 stereographic projections) |
|                     | 1:2,000,000 (topographic)              | 140   |
|                     | 1:2,000,000 (color)                    | 140   |
|                     | 1:25,000,000                           | 1   |
| Io                  | 1:15,000,000                           | 1   |
|                     | 1:5,000,000                            | 3 (2 Mercator, 2 stereographic on one sheet projections)    |
|                     |  |   |
| Europa              | 1:25,000,000                           | 1   |
|                     | 1:15,000,000                           | 1   |
|                     | 1:5,000,000                            | 3 (Mercator, 2 stereographic on one sheet projections)      |
| Ganymede            | 1:25,000,000                           | 1   |
|                     | 1:15,000,000                           | 1   |
|                     | 1:5,000,000                            | 15 (5 Mercator, 8 Lambert, 2 stereographic projections)     |

*Table 6.—Global and Planetwide Mapping Series—Continued*

| Planet or satellite | Scale        | Number of sheets  |
|---------------------|--------------|---|
| Callisto            | 1:25,000,000 | 1   |
|                     | 1:15,000,000 | 1   |
|                     | 1:5,000,000  | 15 (5 Mercator, 8 Lambert, 2 stereographic projections) |
| Mimas               | 1:5,000,000  | 1   |
| Enceladus           | 1:5,000,000  | 1   |
| Tethys              | 1:10,000,000 | 1   |
| Dione               | 1:10,000,000 | 1   |
| Rhea                | 1:10,000,000 | 1   |
| Iapetus             | 1:10,000,000 | 1   |

NOTE: There are no plans to complete all the sheets in some map series, and in others the necessary data will be received from future planned missions.

data and synoptic coverage. Medium- and large-scale maps are of particular interest to planetary geologists as base maps for geologic mapping. They are also important in planning spacecraft landing areas and the surface navigation of rovers.

### 6.7. Summary

Planetary geodesy and cartography continue to supply the basic data products without which detailed geologic investigations of planets and satellites would be impossible.

Geodesy supplies fundamental parameters such as the average radius, shape, and rotation rate of a body, as well as precise determinations of spin axes. Accurate determinations of radii are needed to calculate mean densities from masses and thus obtain information on the general composition (chapter 4). Data on shapes, when combined with density and rotation rate information, can be used to place constraints on the internal structure of an object (chapter 5).

Cartography continues to supply detailed global and regional maps showing the extent and relative locations of surface features and, in the best of cases, their vertical relief. Such cartographic products are essential to geologic mapping and to detailed investigations of the geologic evolution of solid surface bodies, as well as to the planning of future missions. Clearly, a major objective of any exploratory mission in the solar system must be the gathering of data that will permit the required first-order geodetic and cartographic work. Unfortunately, this objective has not always been met

in the past. For example, in the case of Mars, in spite of missions as sophisticated as Viking, we still lack accurate altimetry for most of the planet. This and similar fundamental gaps in our knowledge should be remedied as our efforts to explore the solar system continue. We should also anticipate the need to develop geodetic and cartographic techniques suitable for dealing with small, irregular bodies: asteroids, small satellites, and perhaps even comet nuclei (chapter 7).

## 7 The Geology of Small Bodies

Given that there are thousands of asteroids and probably a hundred thousand million comets, these small bodies must be considered essential components of the solar system. Certainly objects closely similar to the small bodies that remain today were involved in the agglomeration of the larger planets and satellites some 4.5 billion years ago, and much of the importance of the small bodies today derives from the clues that they may contain about the processes that took place in the early solar system. This importance is magnified when we realize that asteroid-like parent bodies are the only solar system objects (other than Earth and the Moon) of which we have samples for detailed laboratory studies.

Although our understanding of small bodies is relatively limited, we know enough to realize that geologically these objects are best studied separately from the larger bodies, such as Earth and the Moon. For one thing, gravity is so much smaller on these bodies that it is difficult to extrapolate our experiences with surface processes on larger objects with any great confidence. For another, many of the small objects are irregular and call for mapping and geodetic techniques quite distinct from those commonly used for the larger (usually almost spherical) planets and satellites.

### 7.1. What is a Small Body?

It is not easy (nor is it necessary) to give a rigorous definition of a small body. Certainly implicit in the term is that the object has a low surface gravity and small escape velocity. Rather arbitrarily, we can take the largest small body to be the size of the biggest asteroid, Ceres, which has a diameter of some 1000 km. Most small bodies are considerably smaller; the two satellites of Mars, Phobos (21 km) and Deimos (12 km), are more representative.



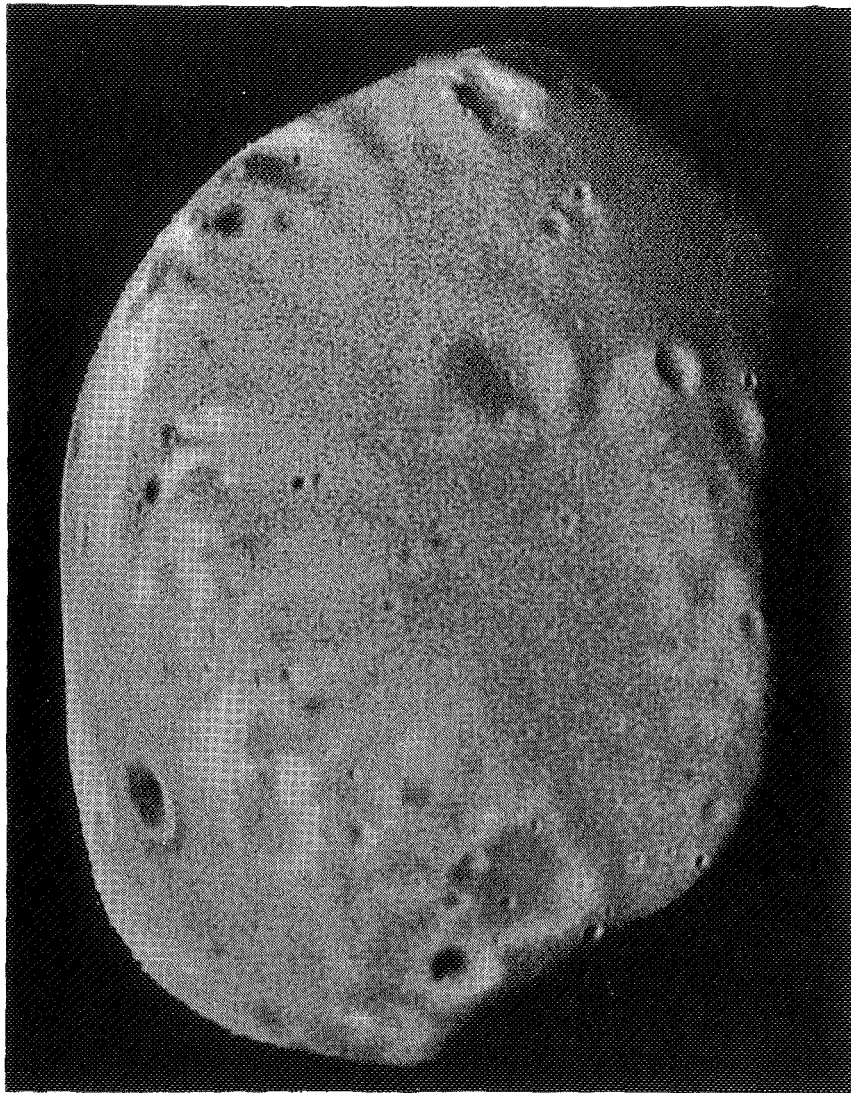
For an object the size of Phobos, surface gravity is only about  $1 \text{ cm sec}^{-2}$ , and the escape velocity is some  $10 \text{ m sec}^{-1}$ . Weak gravity has several important implications. Since such bodies cannot have atmospheres, their regoliths are immune to weathering processes involving the presence of an atmosphere. On the other hand, they are directly exposed to the whole spectrum of meteoroidal impacts, cosmic rays, solar radiation, and the solar wind. Low gravity also makes it impossible for the body to achieve or retain a spherical shape during its history, and many small bodies tend to be irregular in shape. Additionally, low gravity affects the development of the surface under meteoroidal bombardment. Craters probably tend to remain deeper, ejecta become more dispersed, and the proportion of strongly shocked material retained is smaller than on larger bodies. Furthermore, the chances that an asteroid-like small body will suffer a catastrophic, or nearly catastrophic, impact during its history are non-negligible.

The study of meteorites has provided incontrovertible proof that some small parent bodies underwent differentiation (Dodd, 1981). In addition, there is strong evidence of subsurface aqueous processes in some parent bodies (Kerridge and Bunch, 1979) and of surface eruptions of lavas on others (Drake, 1979). The realization of the importance of short-lived nuclides such as  $^{26}\text{Al}$  as possible heat sources early in the solar system's history has made it quite plausible that some small bodies should have had early histories of melting and other internal activity (Sonett and Reynolds, 1979). Thus, whereas some small bodies (comet nuclei?) may have had dull evolutionary histories and may rightly be regarded as primitive, others have probably experienced histories almost as complex and certainly as interesting as some larger objects.

## **7.2. Inventory**

The solar system's small bodies can be divided conveniently into three broad categories: (1) rocky objects (asteroids and some small satellites), (2) icy objects (mostly small satellites, but perhaps including such objects as Chiron), and (3) comet nuclei.

The inventory of known small bodies includes thousands of asteroids in the main belt, as well as about 60 Amor, Apollo, and Aten objects. Only about 35 asteroids are larger than 200 km across, although physical measurements have been made of objects as small as 200 meters (Gehrels, 1979). None has yet been studied by spacecraft.



*Mars' outer satellite Deimos, a body only 12 km across.*

The inventory also includes the small satellites of Mars and of the outer planets. Phobos and Deimos, the two tiny satellites of Mars, are the only very small bodies that have been investigated sufficiently by spacecraft (Mariner 9 and Viking) to permit meaningful discussions of surface geologic processes (Veverka and Thomas, 1979).

Jupiter has at least a dozen small satellites. Except for a few low-resolution images of Amalthea obtained by Voyager, we know

almost nothing about the geology of these bodies. There are also at least 70 known Trojan asteroids near the libration points of Jupiter's orbit, and speculations exist that some of Jupiter's outer satellites may be related to them (Degewij and van Houten, 1979).

Recent Earth-based and Voyager observations have greatly expanded our list of Saturn's small satellites, and at least in the case of Mimas and Enceladus, the Voyager data are adequate to support geologic investigation. Beyond Saturn, most of the satellites of Uranus, Neptune's Nereid, and Pluto's Charon probably fall within our definition of small bodies. However, it will be at least 1986 before any spacecraft data on any of these objects are available.

It is worthwhile to stress that the above list is almost certainly incomplete and that new small bodies will continue to be discovered. In addition, there are indications that small, so far undetected, satellites are associated with the rings of Uranus and perhaps those of Saturn and Jupiter as well.

Comets are the most abundant small bodies in the solar system: one estimate is that some  $10^{11}$  exist in the Oort cloud at the fringes of the solar system (Wilkening, 1982). From the geologic point of view, it is only the nuclei of comets that are of interest and not the comas and tails that develop when the nucleus approaches close enough to the Sun for its surface ices to vaporize. Most comet nuclei are believed to be bodies of rock and ice less than 10 km across, but very little direct information about them exists. None has been studied by spacecraft yet. They could be the parent bodies of some volatile-rich meteorites, and there may be an evolutionary connection between them and some asteroids. For example, it has been suggested that some Apollo asteroids are the remnants of extinct short-period comets (Shoemaker and Helin, 1977; Kresak, 1979).

In summary, three facts about small bodies must be kept in mind: (1) their vast number, (2) their great diversity, and (3) our lack of knowledge concerning them.

The next two decades of solar system exploration should remedy our current lack of information about small bodies. We cannot gain a true understanding of the solar system's evolution by ignoring them. They are of interest not only in their own right, but as the solar system's most abundant projectiles, they have influenced, in some cases probably dramatically, the evolution of the surfaces of the larger planets and satellites.

### 7.3. Why Study Small Bodies?

At least four major reasons for studying small bodies in the geologic context can be given:

1. Small-body impacts have significantly modified most planetary and satellite surfaces. Data on present and past fluxes and size-frequency distribution are essential to a thorough understanding of the chronology and evolution of such surfaces.
2. It is likely that there are geologic processes that are effective on small bodies, but that cannot be studied adequately on larger objects.
3. Owing to the wide range of surface characteristics ( $g$  varying from about  $100 \text{ cm sec}^{-2}$  to less than  $0.1 \text{ cm sec}^{-2}$ , and composition varying from metallic to icy), small bodies provide a unique laboratory for calibrating the dependence of basic planetary processes, such as cratering, on different variables.
4. A better understanding of the geologic evolution of small bodies is needed to better define their possible interrelationships and to take full advantage of the information provided by the meteorite record.

It could also be argued that another important reason for studying small bodies is that their geologic record may extend further back in time than that preserved on the surfaces of the larger bodies. Also, many small bodies (including satellites) probably are collisional fragments of large bodies and in some instances could provide accessible information on the differentiation of large parent bodies.

#### ***7.3.1. Effects of Small Bodies on Larger Objects***

Surfaces in the solar system continue to be modified by impacts, and there is abundant evidence that during the first half billion years of the solar system's existence, the surfaces of planets and satellites were influenced dramatically by collisions with small bodies. From the geologic point of view, we are interested in the time history of the flux and population (size and composition) of the impacting objects at different distances from the Sun. The early fluxes appear to have had a profound influence on the evolution of the crusts of larger bodies, and subsequent fluxes are important in

determining relative chronologies of different surface units (chapter 3). The actual nature of the impacting bodies (whether volatile-rich or volatile-poor) may have played a role in determining the evolution of some atmospheres and perhaps even of subsequent weathering processes. For instance, it has been proposed that a significant fraction of some gases in the atmospheres of the terrestrial planets were brought in by comets.

Some of the important questions to be addressed are:

1. What is the present flux of small bodies in Earth's neighborhood? What is the current proportion of volatile-poor and volatile-rich objects?
2. How have this flux and the proportion of volatile-poor to volatile-rich objects changed with time?
3. How do these quantities presently vary throughout the solar system? How did they vary in the past?
4. What have been the mechanisms responsible for the changes in the impact flux, if such changes have occurred?

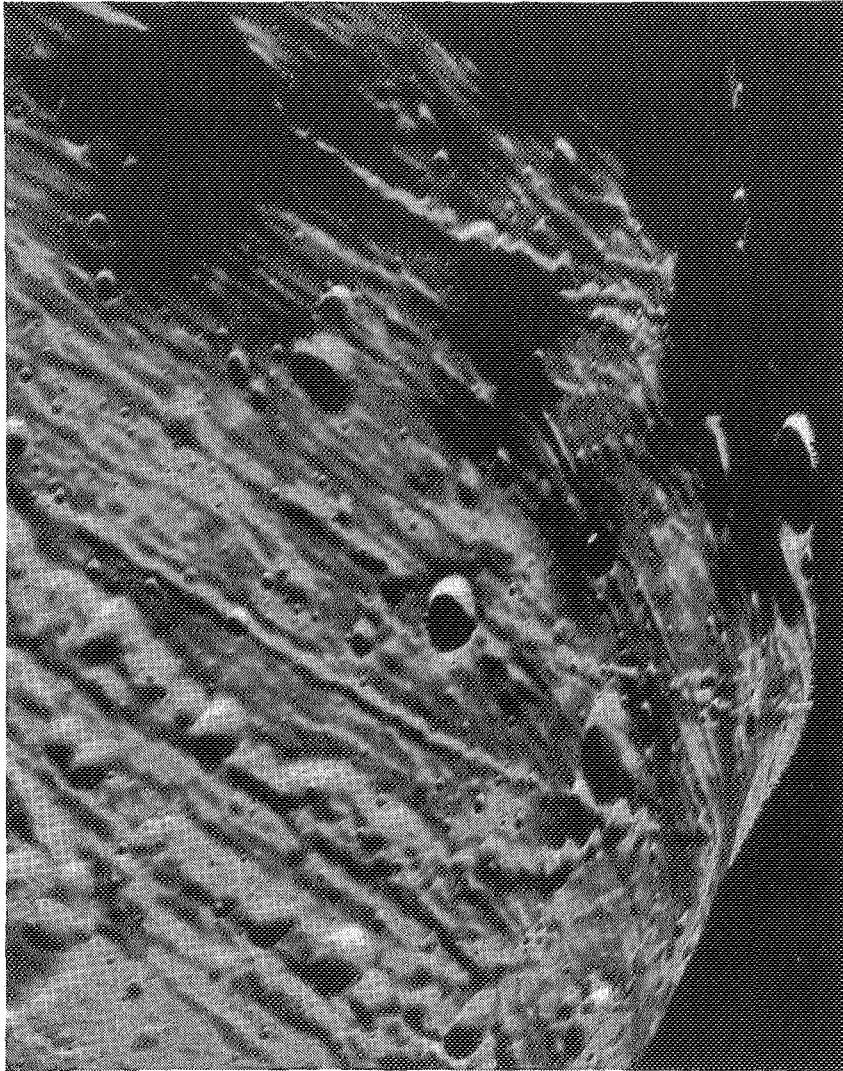
In the above, the term "flux" should be understood to mean not only total flux of bodies of all sizes (or masses) but also information about the relative fluxes of bodies of various sizes (or masses).

A vigorous program of searching for Apollo, Aten, and Amor asteroids, as well as for comets, can answer the first of these questions. The second and third questions are more difficult, but considerable progress is being made in addressing some aspects of them by theoretical calculations.

A closely related issue involves the orbital evolution of the various classes of impacting objects (origin, lifetime, and eventual fate). For example, how do objects end up in Apollo orbits? How long do they stay? What happens to them?

### ***7.3.2. Unique Surface Features and Processes***

Not surprisingly, there are processes that are important on small bodies but impossible to predict from an extrapolation of our terrestrial or lunar experience. In fact, it is sometimes even difficult to predict a priori what form a well-known process will take in the small-body environment. For example, a decade ago, there was a legitimate discussion about whether or not there would be recognizable craters on bodies as small as the satellites of Mars. A more serious debate developed about whether appreciable regoliths would form on such small objects. Although we have now learned



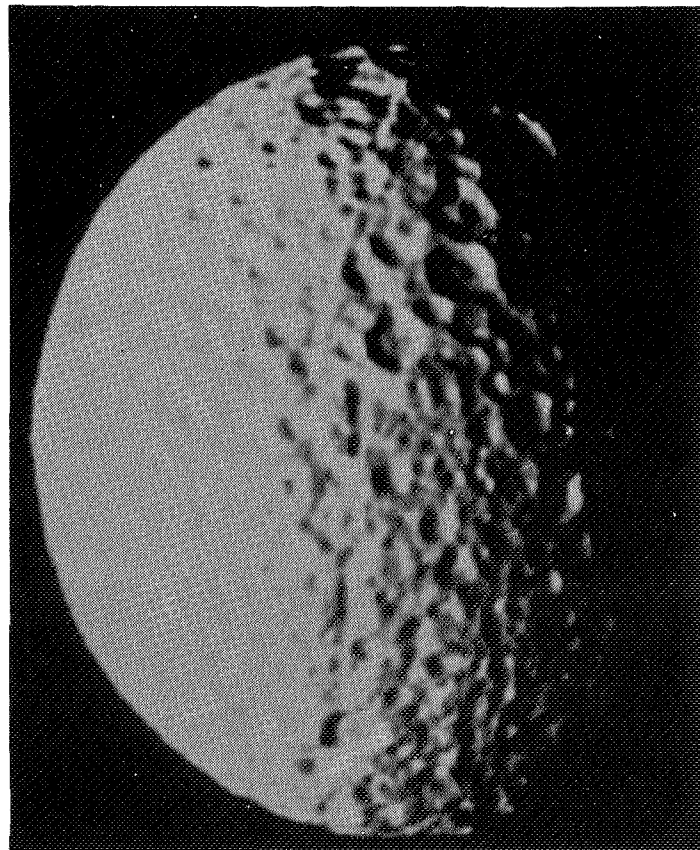
*The unexpected grooves of Phobos.*

the answers to such rudimentary questions, we cannot pretend to fully understand the process of cratering and regolith formation on small bodies (Cintala et al., 1978; Housen and Wilkening, 1982). For example, we have no convincing explanation for the grossly different appearance of the surfaces of Phobos and Deimos. Why is it that the surface of the smaller Deimos appears to have retained considerably more regolith than that of the larger Phobos?

Our very limited experience in exploring small bodies has already confirmed that unique and unexpected surface features and processes come into play. No one anticipated the existence of grooves on Phobos, yet this type of feature may well be a common one on many small bodies (Thomas and Veverka, 1979). There is every reason to expect that additional, important surface features and processes will be discovered as our exploration of small bodies proceeds, especially in the cases of small icy satellites and the nuclei of comets.

### ***7.3.3. Small Bodies as Natural Laboratories***

Due to their great diversity in size and composition, small bodies provide ideal testing grounds for studying various processes, especially those involving cratering. In principle, one can find small



*Mimas, a small icy satellite of Saturn.*

bodies of similar surface gravity but drastically different surface composition (rock versus ice), or bodies of similar composition but very different surface gravity, to test the importance of such variables on crater morphology, ejecta patterns, etc. Much could be learned by comparing surface features and regolith characteristics on three small asteroids of similar surface gravity but of different composition (carbonaceous, stony, or metallic). As a next step, one could investigate the effects of rotation rate on regolith characteristics by comparing two asteroids that are identical in all bulk characteristics except their spin rates. Full exploitation of such possibilities would require an aggressive program of future solar system exploration.

#### ***7.3.4. Evolution and Interrelationship***

There is ample evidence that some small bodies have had complicated evolutionary histories that involved processes of high interest to planetary geologists. The meteorite record proves that some parent bodies experienced internal differentiation, aqueous metamorphism, and even the eruption of lava onto their surfaces (Dodd, 1981). In many cases, very mature and very complex regoliths were developed (Housen and Wilkening, 1982). Understanding the geologic evolution of such interesting bodies is not only worthy in its own right, but would improve our understanding of the possible interrelationships among small bodies and between the small bodies and larger planets. First, there are questions of the following type to be considered: what styles of eruption and what types of volcanic constructs would one expect on a body as small as Vesta? Or, what kinds of structure control the local emission of gases from a comet nucleus? Second, there are the interrelationship questions; for example, is it geologically reasonable that a comet nucleus can evolve into something like an Apollo asteroid or that some volatile-rich carbonaceous chondrites could come from comets? Unfortunately, in many cases we still lack key observational data to address such important questions meaningfully.

#### **7.4. Summary**

The small bodies of the solar system are of great intrinsic geologic interest that goes beyond their original role as building blocks of planets and their subsequent role as projectiles. They are characterized by vast numbers and by their diversity.



So far, their geologic study has been hampered by a lack of first-hand information of the sort that can be obtained only by direct spacecraft exploration. Even after Viking and Voyager, our inventory of small objects about which enough is known to carry out detailed geological investigations is very meager. It is restricted to a few icy satellites of Saturn and to the two rocky moons of Mars. We have yet to carry out a geologic reconnaissance of an asteroid or a comet nucleus. Although our accumulated knowledge may be adequate to guess what asteroid surfaces may be like in a general way, we really know next to nothing about comet nuclei. Thus, a first-order requirement for progress in our understanding of small bodies is the exploration of at least one asteroid and one comet nucleus during the coming decade. Some important questions, however, can be addressed only by studying a variety of objects.

In the meantime, it is important to continue the ongoing active programs of Earth-based observations of small bodies as well as related laboratory and theoretical investigations. It is especially crucial to continue monitoring the neighborhood of Earth's orbit for small comets and asteroids, since there is no other way of obtaining adequate statistics on the population of such objects.

In terms of data analysis and interpretation, there are enough unresolved questions concerning the small satellites of Mars and of the outer planets to justify a healthy program of analysis of Viking and Voyager data in these areas. For example, the Viking IRTM\* measurements of Phobos and Deimos must be fully correlated with imaging data to gain information on regolith characteristics. We must also develop techniques for mapping irregular satellites and making accurate measurements of their topography and volume. We should make a special effort to apply the many lessons we have learned from comparative planetology during the past two decades to considerations of surface and near-surface processes on small bodies. Such extrapolations from our experience with larger bodies will have to be done judiciously, but the effort should prove beneficial to our general understanding of the solar system.

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\*Infrared Thermal Mapper.

## **8 Remote Sensing and Supporting Earth-Based Studies**

Traditionally, progress in planetary geology has resulted from an active interplay between the study of the surfaces of distant objects and detailed field work, laboratory investigations, and supporting remote sensing measurements here on Earth. We expect this close interrelationship to continue in the future.

The purpose of this chapter is to outline some directions that we see such studies taking during the next decade in support of the planetary geology goals outlined in the preceding chapters. The three major areas involved: (1) terrestrial analog studies in the field; (2) laboratory measurements and simulations; and (3) remote sensing observations, are discussed in turn in the following sections.

### **8.1. Analog Studies**

In this report, we have laid great stress on understanding planetary processes by analogy with those observed on Earth. This procedure has obvious advantages and has proven its value during the past twenty years. First, Earth's surface is far more accessible for detailed investigation of common processes than that of any other planet. Second, due to this ready accessibility, the range of applicable techniques and instrumentation is far wider. Third, in view of the different surface environments involved, detailed comparisons of similar processes on Earth and other planets often make it possible to assess the relative importance of the many variables that might affect a particular process. Specific examples of important analog studies that should be carried out are described in chapter 2 and chapter 4. The Planetary Geology Working Group stresses the fundamental importance of such analog studies to the continued

vigorous development of our field. As our understanding of the planets increases, our ability to ask incisive questions grows: the process is an evolving one.

## **8.2. Laboratory Studies**

In many scientific disciplines, laboratory simulations and experiments serve as an essential bridge between observation and theory. This remark is especially true of many branches of planetary geology, in which time scales ranging from microseconds to billions of years, processes varying across scales of micrometers to the dimensions of the solar system, and environments as disparate as the surfaces of asteroids and of Venus must be treated. The exploration of the solar system continues to challenge present theories and models with observations of processes that are beyond our immediate experience and intuitive grasp. In such cases, laboratory work is of utmost importance. Some examples, chosen from different areas of planetary geology, are discussed below.

### ***8.2.1. Cratering***

Insofar as craters are the most ubiquitous landform in the solar system, it is not surprising that impact cratering was one of the first planetary geology processes to be simulated in the laboratory. In particular, the light gas gun at the NASA Ames Research Center (e.g., Gault et al., 1968) was designed and built specifically for this purpose in the early 1960s. It remains the principal facility for impact cratering experiments under simulated planetary conditions and serves as an excellent example of a laboratory facility designed to investigate a fundamental planetary process. Not only can projectile size, shape, composition, velocity, and impact angle be controlled, but a wide variety of targets can be used in a vacuum chamber equipped with high-speed motion picture equipment. Additionally, targets can be dropped at various accelerations during impact experiments to simulate different gravitational fields, ejecta kinematics and characteristics can be documented through various techniques, and the resulting craters can be preserved and dissected to investigate subsurface phenomena.

Work at this facility and the results of impact and explosion experiments elsewhere have yielded extremely important data on how various parameters influence the cratering process (Roddy et al., 1977). These results, in turn, have been applied to the study of

much larger craters. However, to date, the bulk of the experiments involved rocky materials. Following Voyager's investigations of the satellites of Jupiter and Saturn, there is an immediate need to carry out similar experiments to understand cratering in ice and ice-rich targets. Comprehensive programs to determine the equations of state of planetary materials under high shock stress conditions will also contribute toward our overall understanding of this ubiquitous planetary process.

### ***8.2.2. Volcanic Processes***

It is clearly difficult to simulate volcanic processes in the laboratory. Much attention must be paid to detailed scaling to guarantee effective modeling. Before reliable volcanic models can be constructed, the properties of magmas, lavas, and hot solids must become better known over the wide range of complex conditions of interest in planetary processes. Volatile content, eruption temperature, density, specific heat, yield strength, thermal conductivity, and temperature dependence of viscosity are but a few of the quantities necessary to describe the physical state of a volcanic liquid or a hot particle suspension. As might be expected, only a few of these variables can be controlled at any one time during a modeling experiment.

In spite of these difficulties, laboratory models such as those being developed by Greeley and co-workers (Womer et al., 1980) provide the potential to understand in much greater detail the phenomena associated with planetary-scale silicate volcanism. Such work should be extended to other eruptive processes (sulfur volcanism on Io, ice volcanism on the icy satellites, etc.).

### ***8.2.3. Tectonics***

Because of their large scales, tectonic features are difficult to simulate in the laboratory. Nevertheless, laboratory-derived data on the behavior of various geologic materials are important in constraining hypotheses that attempt to explain tectonic forces, mechanisms, and the resulting structures. Information on the mechanical properties of various materials of planetary interest under diverse conditions are needed. For example, in the context of the outer planet satellites we need information on low-density materials such as ice, ice-clathrates, salts, and ice-rock mixtures at very low temperatures. In the context of Venus we need data on the properties of hot silicates over a wide range of confining pressures.

#### **8.2.4. Fluvial Processes**

As a result of various engineering, geomorphologic, and hydrologic studies, a wealth of fluid mechanical data exists for direct application to planetary problems of fluid flow. Yet there remain many planetary geology questions concerning fluvial processes that can most readily be answered by laboratory studies. For instance, what would be the characteristics of a liquid methane flow on the surface of Titan? What might have been the behavior of a suspension of ice particles and silicate grains in turbulent flow on the surface of Mars? How would the erosional efficiency of such flows vary as a function of substrate structure, slope, and other variables?

#### **8.2.5. Aeolian Phenomena**

The details of wind-related processes are often so complex that they require laboratory simulations to describe them adequately. Although the flow patterns around geometrically uniform objects have been studied thoroughly, this is certainly not the case for irregularities associated with craters, hills, canyons, and other geologic features. Thus, the resolution of conflicting interpretations of specific erosional and depositional features on Earth and Mars will rely on scale-model or other simulations.

Environments that will be equally challenging in terms of eolian processes are those presented by Venus and Titan. Although the surface environment of Titan remains poorly known, the eolian regime on Venus is reasonably well defined. Specialized wind tunnel facilities currently under development should contribute substantially to our understanding of wind-related erosional and depositional phenomena under Venus' extreme pressure and temperature conditions (e.g., Greeley et al., 1980b).

#### **8.2.6. Cometary Processes**

Cometary nuclei are bodies with which we have no geologic experience. Their inferred weak, volatile-rich structure and exceedingly small gravitational fields undoubtedly give rise to unusual processes that have no immediate analogs on the larger, more familiar bodies of the solar system. Due to the current lack of hard data on the properties of comet nuclei, it is difficult to suggest specific topics for laboratory studies at the present time.

#### **8.2.7. Regolith Processes**

Laboratory simulations provide unique means of studying regolith and weathering processes (e.g., Huguenin, 1973a, 1973b, 1978).

Three types of questions can be addressed by such experiments:

1. Types of alteration and weathering products as a function of environmental conditions.
2. Rates of alteration and weathering reactions as a function of environmental conditions.
3. Reaction mechanisms.

For many planetary bodies the environmental parameters are not known in detail. More importantly, the interactions of the sample and environment are complex. Consequently, more than one set of experimental parameters will often produce reasonable agreement with the ground-truth data within the constraints of our current knowledge of environmental conditions.

The applicability of the results of simulation studies will depend directly on how accurately the environmental conditions can be reproduced in the laboratory. These conditions include temperature, pressure, composition of the gas atmosphere, the spectral distribution and flux of the electromagnetic radiation impinging on the surface, and the normal planetary variations in these parameters. It is not necessary or even desirable, however, to exactly reproduce some of the environmental parameters if they can be scaled.

### **8.3. Remote Sensing**

Remote sensing measurements have played a key role in the development of our ideas about the geologic nature of the planets and satellites in our solar system. Although such observations, either from Earth or from a spacecraft, do not fall within the traditional techniques of geology, they nevertheless continue to provide essential data about the surface environments of the bodies we study.

Conventionally, remote sensing techniques are classified to first order by the spectral range in which they operate and then according to the spectral resolution they employ. On such bases, one finds terms such as photometry, colorimetry, spectral reflectance, spectroscopy, infrared radiometry, radar, etc.

Radar and radio remote sensing have provided important data of geologic interest and are discussed in a separate section below. Remote sensing of X-rays and  $\gamma$ -rays from lunar orbit have provided essential information about the distribution of rock types on the Moon (Adler et al., 1972; Arnold et al., 1972). Infrared radiometry

has provided unique data about the texture of planetary and satellite surfaces from observations such as the eclipse cooling and post-eclipse heating rates of the Galilean satellites (Morrison, 1977). It has provided one of the most reliable means of determining the sizes and albedos of asteroids and other small, remote objects (Morrison and Lebofsky, 1979). It has been used to monitor the extent of volcanic activity on Io, and, in one of its most sophisticated developments to date, the Viking IRTM\* experiment (Kieffer et al., 1976), it provided numerous invaluable pieces of information about Mars: surface temperatures, textures, atmospheric opacity, etc.

Since gases display much sharper spectral features than solids, the highest spectral resolution measurements (spectroscopy) are often devoted to investigations of atmospheric composition and structure, topics that are of interest to planetary geology only insofar as they relate to the surface environment of the planet, rates of weathering, and possibly to rates of outgassing. Nevertheless, spectral measurements at high wavelength resolution have produced, and will continue to produce, some data of crucial importance to the geologic studies of the planets. Examples include the Mariner 9 IRIS† spectral constraints on the composition of the dust in Mars' atmosphere (Hanel et al., 1972), the detection and monitoring of sodium, sulfur, and other clouds in the vicinity of Io's orbit (Pilcher and Strobel, 1982), as well as the very high resolution infrared spectra of satellites and asteroids obtained by Larson and Fink, Pilcher, Ridgway, and others (e.g., Pilcher et al., 1972; Fink et al., 1973; Larson and Veeder, 1979). Our basic knowledge that many of the satellites of the outer planets have surfaces made of water ice comes from such observations (Sill and Clark, 1979; Cruikshank, 1979, 1980).

Generally speaking, the spectral region between 1 and 5 micrometers ( $\mu\text{m}$ ) is the most diagnostic in terms of composition of solid surfaces. Important Earth-based measurements in this region include the detection of  $\text{SO}_2$  frost as a major constituent of Io's surface (Fanale et al., 1979; Nash and Nelson, 1979) and the discovery of methane frost on the surface of Pluto (Cruikshank et al., 1976). Such measurements have also been used to demonstrate that the surface of Ceres, the largest asteroid, is similar in composition to some type 2 carbonaceous chondrites and that it certainly con-

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\*Infrared thermal mapper.

†Infrared interferometer spectrometer.

tains water of hydration and perhaps even particles of surface frost (Lebofsky, 1978, 1981). They have also been used in attempts to match the spectral colors of the dark side of Iapetus with those of Phoebe (Cruikshank et al., 1982) and in attempts to understand the composition of the residual caps on Mars (Clark and McCord, 1982). Fundamentally new information will come when instruments such as the Galileo Orbiter NIMS\* will be able to make spectrally resolved maps of objects within the 0.7 to 5  $\mu\text{m}$  window.

Most of the remote sensing observations shortward of 1  $\mu\text{m}$  can be conveniently divided into photometry, colorimetry, and spectral reflectance measurements. The actual wavelength range covered by most of these observations is about 0.3 to 1.2  $\mu\text{m}$ , due to a combination of three main factors: transparency of Earth's atmosphere, spectral range of common detectors, and spectral distribution of the Sun's energy. Generally speaking, measurements below 3000 Å, although of crucial importance to the remote sensing of atmospheres, are not of prime importance to the study of solid surface. However, important exceptions exist; for example, the detection of SO<sub>2</sub> frost on the trailing hemisphere of Europa by Lane et al. (1981) using observations made by the IUE† spacecraft.

Photometry of planetary and satellite surfaces may be defined as the study that aims to determine how a particular surface scatters incoming sunlight (e.g., Veverka, 1977). The result is usually expressed in the form of a photometric function, which may or may not depend significantly on the wavelength. Understanding how the surface of an object scatters incident sunlight is one of the fundamental parameters about it that we must know. Such knowledge is needed to determine accurately the albedos and colors of the various surface units and is a prerequisite to the construction of meaningful albedo and color maps. Precise albedos and photometric functions are also needed to calculate accurate values of surface temperatures, which are essential to discussions of the stability of frosts on various surfaces (e.g., SO<sub>2</sub> frost on Io, H<sub>2</sub>O frost on the surface of Callisto, etc.). Accurate albedos may also be useful in answering important specific questions, such as, is Phoebe dark enough to be the source of some of the dark material on the leading hemisphere of Iapetus (Thomas et al., 1983)?

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\*Near-infrared mapping spectrometer.

†International Ultraviolet Explorer.



Photometric measurements also provide information on the texture of surfaces. Although there is some debate on how uniquely such information can be extracted from photometric data, there is no question that such determinations are useful in a comparative sense. Thorpe (1978) has attempted to derive the relative textures of certain eolian features on Mars from their photometric behavior, whereas Bowell and Lumme (1979), as well as others, have used disk-integrated measurements to compare the surface textures of various minor planets. Information on the texture of surfaces has also been inferred in the past from measurements of the degree of linear polarization of the scattered sunlight, but in recent years such polarization measurements have been used mostly to estimate the albedos, and hence sizes, of numerous minor planets (Zellner, 1979).

Colorimetry is the term used to describe broadband measurements of the colors of planets or of individual features on their surfaces. As the spectral resolution of such measurements increases, colorimetry merges into spectral reflectance measurements. Typical spectral resolution in spectral reflectance measurements is between 0.02 and 0.1  $\mu\text{m}$ , the common spectral interval covered being approximately 0.3 to 1.2  $\mu\text{m}$ . Among the very important spectral reflectance measurements made during the past decade, one must single out the work of McCord and his many co-workers dealing with the Moon, Mars, asteroids, and satellites (e.g., McCord et al., 1982a, b). Such data have been used to correlate spectral properties with the geologic character of lunar surface units and features (Adams and McCord, 1970; Head et al., 1978; Pieters et al., 1980, 1981), and have served as the basis for inferring the compositions of many asteroids (Chapman and Gaffey, 1979; Gaffey and McCord, 1979). Perhaps the most famous single result obtained by this technique was the identification of the surface of Vesta as corresponding to a basaltic achondrite (McCord et al., 1970). The important information that there is a gradation in asteroid composition with increasing distance from the Sun in the asteroid belt also comes in part from such measurements (Gradie and Tedesco, 1982).

Even though our progress in the direct exploration of the planets and satellites has been phenomenal during the past fifteen years, the role of remote sensing in studying these objects cannot be expected to diminish in the future. We cannot expect to send spacecraft to all the bodies in the solar system about which we

require information. This comment applies especially to the multitude of small bodies, asteroids, and comets discussed in chapter 7. We also must anticipate that the power of remote sensing techniques will continue to grow in the future, as will the ability of such techniques to address important new questions in the context of planets and satellites that our spacecraft have visited in the past. Inevitably, most spacecraft in the past have carried remote sensing instruments of interest to planetary geology. Certainly, this trend will continue in the future.

### ***8.3.1. Remote Sensing Using Earth-Based Telescopes***

In spite of the continuing direct exploration of planets, there remain key remote sensing observations to be made by Earth-based and airborne telescopes working in the ultraviolet, visible, and infrared parts of the spectrum. The following brief list is meant to be illustrative, rather than exclusive. The PGWG\* has made no attempt to attach relative priorities; the discussion is given in order of increasing distance from the Sun.

*Moon.* We expect the Moon to continue to be a focus for many remote sensing efforts, both in support of increasingly detailed geologic investigations and as the diagnostic sensitivity of our techniques continues to improve. These efforts will continue to provide important new information (e.g., Pieters, 1981).

*Mars.* Efforts to monitor the overall appearance of the surface of Mars (extent, color, and albedo of major markings; maximum extent and recession of the polar caps), as well as the state of the atmosphere (dust storms, polar hoods, general opacity) should continue. Additional spectral mapping of individual regions is also needed.

*Mars Satellites.* The major outstanding data that can be obtained using state-of-the-art instrumentation are accurate spectra of Phobos and Deimos between 0.4 and 1.2  $\mu\text{m}$  (at least). The optimum time to carry out such measurements will be during the favorable oppositions of the mid-1980s.

*Asteroids.* Statistics on Earth- and Mars-crossing asteroids should be augmented. The gathering of high-quality spectral reflectance curves of minor planets should continue, with special attention to faint but important objects such as the Trojans, Apollos, and Atens.

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\*Planetary Geology Working Group.

Improved determinations of asteroid sizes, shapes, and spin rates are of interest in understanding the collisional evolution of the asteroid belt.

*Io.* A major effort is needed to monitor Io's volcanic activity by means of infrared radiometry (Sinton, 1980). Complementary high-resolution spectroscopy as a function of orbital longitude could yield information on possible changes in the areal extent of SO<sub>2</sub> frost deposits in response to variations in volcanic activity.

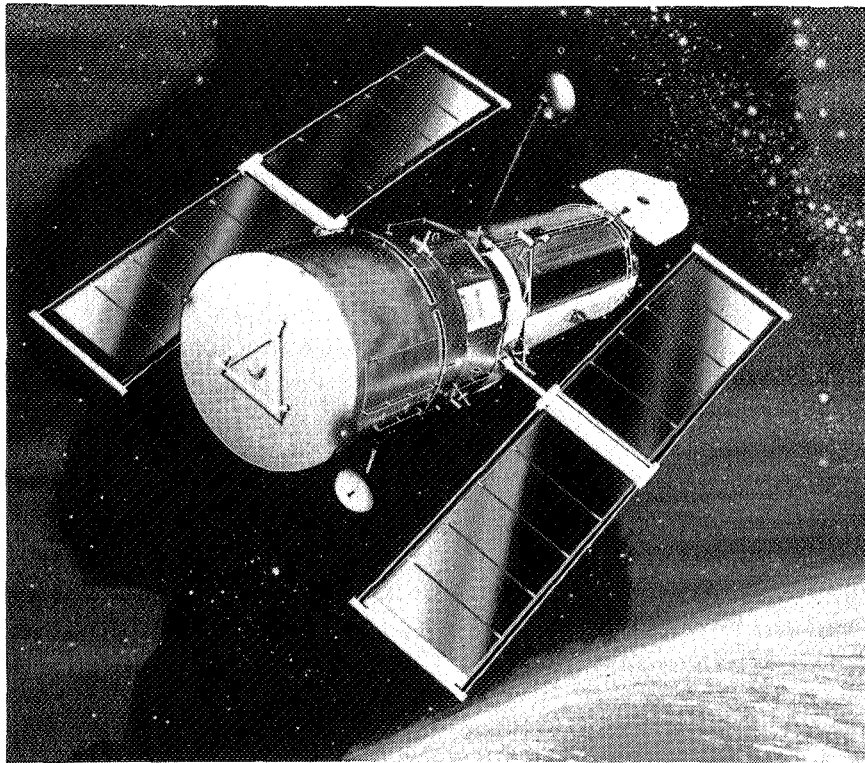
*Outer Planet Satellites.* The single most important task in this area is to obtain high-resolution spectra in the visible and infrared to define surface compositions as well as possible. Whenever practicable, such data should be obtained as a function of orbital longitude to look for surface heterogeneity. Special attention should be devoted to the little-studied faint satellites. For example, some of the important questions concerning the small satellites in the Jupiter system that can be addressed are: (1) How similar are the surfaces of the outer satellites, and how do they compare with those of the Trojans? (2) How similar are the surfaces of the newly discovered small inner satellites, and how do they compare with that of Amalthea?

*Pluto System.* So little is known about the Pluto/Charon system that any sort of quantitative information is highly desirable. Since Pluto's distance from the Sun changes appreciably, it is important to monitor this planet over periods of decades to see if any noticeable changes in its lightcurve or in the amount of CH<sub>4</sub> in its atmosphere occur in response to changing insolation.

*Comets.* From the point of view of planetary geology, it is comet nuclei and their possible evolutionary connection with certain types of asteroids that are of major interest. Good statistics on the sizes and rotation rates of cometary nuclei are needed for comparison with asteroid data, as are high-quality spectral reflectance measurements.

### **8.3.2. Observations from Earth Orbit**

Many of the objectives outlined in section 8.3.1 can also be addressed by instruments in Earth orbit. However, due to potentially higher spatial resolutions and spectral coverage, such instruments can carry out additional investigations that are not possible from the Earth's surface. As an example, we discuss some observations of high interest to planetary geology that could be carried out by Space Telescope in the second half of the 1980s.



*NASA's Space Telescope, scheduled for launch in 1986.*

Space Telescope is a 2.4 m Ritchey-Chretien reflecting telescope that, together with a complement of five optical science instruments, is scheduled to be placed in orbit (approximately 400 km above Earth's surface) by 1986. The first-generation set of instruments includes two imaging systems, the wide field/planetary camera and the faint-object camera; two spectrographs, the faint-object spectrograph and the high-resolution spectrograph; and a high-speed photometer. In addition, the fine guidance subsystem can be used for astrometric measurements. A complete description of the Space Telescope science instruments can be found in Bahcall and O'Dell (1979).

The imaging capabilities of the Space Telescope will exceed those of ground-based telescopes both in spatial resolution and spectral coverage (except in the infrared region of the spectrum). For example, the planetary camera has a spectral range extending from 1150 to 11 000 Å and a picture element (pixel) size that

equals 40 km/AU when projected on the target. Because the modulation transfer function (MTF) of the planetary camera CCD\* is so superior to the vidicons flown on Mariner, Viking, and Voyager spacecraft, the actual resolution of a single frame is likely to be equivalent to that of a vidicon operating at 60 rather than 80 km/line pair/AU. Due to Space Telescope's subpixel pointing accuracy, it will be possible to reach resolutions of 40 km/line pair/AU by adding several images of a target.

The planetary camera can carry out many observations of high interest to planetary geology. Examples include the following.

*Mercury.* Less than half of Mercury was imaged by Mariner 10. Space Telescope could observe Mercury near greatest elongation (typical distance,  $\sim 1$  AU) with a resolution of about 40 km/line pair. At this resolution it should be possible to map features larger than about 100 km, including large craters, basins, and plains units.

*Io.* Space Telescope provides a unique opportunity to monitor volcanic activity on Io and associated changes in surface albedo patterns. Io can be observed from a range of 4 to 5 AU, corresponding to resolutions of 160 to 200 km/line pair.

*Asteroids.* Main belt asteroids can be observed at a range of about 1.5 AU, yielding resolutions of 60 km/line pair. The image of a 300 km asteroid would subtend 10 pixels, whereas Ceres, the largest of the asteroids (diameter=1000 km), would span 33 pixels. Such images can provide unique information on the shapes of the larger asteroids as well as on the albedo heterogeneity of their surfaces. Space Telescope will also provide an unequivocal answer to the question of whether multiple asteroids really exist.

*Mars.* Mars can be observed at ranges of 0.5 to 1.5 AU, corresponding to resolutions of 20 to 60 km/line pair, adequate to monitor global atmospheric activity as well as seasonal variations in the polar caps and albedo markings.

### **8.3.3. Radar and Radio Observations**

Although early radio measurements provided some important information about the planets (e.g., the temperature of the surface of Venus), recently the more exciting results have come from radar observations. The list of impressive firsts includes measurement of spin rates for Mercury, Venus, and several asteroids; altimetry of Mercury, Venus, Moon, and Mars; imaging of Venus; and determi-

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\*Charge-coupled device.

nation of the surface scattering characteristics of Mercury, Venus, Moon, Mars, Galilean satellites, Saturn's rings, and several minor planets (Pettengill, 1978; Pettengill and Jurgens, 1979; Campbell and Burns, 1980; Ostro, 1982, etc.). It should also be noted that radar ranging provides the basis of many highly accurate ephemerides.

At present, there are two facilities in the United States that have the capability to conduct radar astronomy observations: the National Astronomy and Ionosphere Center in Arecibo, Puerto Rico, and the NASA Deep Space Instrumentation Facility in Goldstone, California. The two observatories differ in several respects. Arecibo is equipped with L- and S-band radars and Goldstone with S- and X-band. The Arecibo S-band system is more sensitive by about 7 db than the Goldstone S-band system. Whereas the Goldstone system can track targets from horizon to horizon, the Arecibo coverage is limited to 20° about the zenith.

From Arecibo, Venus and Mercury will be visible periodically during the 1980s, but Jupiter and Saturn will be largely inaccessible; Mars will be a difficult target until late in the decade, but the Moon and numerous minor planets will be readily observable. Mapping of Venus will continue to complement the Pioneer Venus observations, and in support of future missions. Backscatter maps, topography, and surface properties may also be obtained for Mercury, especially in those areas for which Mariner 10 imaging does not exist. Acquisition of the Mars topographic data will continue. New experiments (initiated at Arecibo in 1980) on depolarizing and diffuse scattering properties of Mars' surface should provide new data on the distribution of small-scale (meter-sized) surface structures.

Radar observations of comets and asteroids will also be pursued vigorously at Arecibo throughout the 1980s. (By 1982 over a dozen asteroids and two comet nuclei had been investigated from Arecibo.) These observations will yield basic parameters such as size, shape, and scattering characteristics of these objects. They may also distinguish iron-rich from iron-poor regoliths and set stringent constraints on the existence of satellites of minor planets.

Since the Goldstone antenna is steerable, every solar system object visible in the northern sky is, in principle, available. Goldstone observations of Mercury in the 1980s should yield topographic profiles in the planet's equatorial region and refined determinations of the planet's figure and spin vector.

Three major experiments involving Venus are under consideration at Goldstone: (1) continued S-band tristatic observations, which would yield high-resolution (down to 1 km) topographic and back-scatter maps of the equatorial regions; (2) dual S- and X-band altimetry along the sub-Earth track to improve planetary ephemerides and verify both the Pioneer Venus altimetry and the Goldstone tristatic altimetry; and (3) use of the X-band to detect possible precipitation in the Venus atmosphere.

Goldstone ranging of Mars started in 1971, and by the mid 1980s one complete cycle of latitude coverage will have been completed. One full cycle of martian oppositions, spanning a period of fifteen years, is required to complete coverage of the  $\pm 23^\circ$  latitude band visible to radar from Earth. The X-band observations will have a higher signal to noise ratio, whereas the dual S- and X-band measurements may provide insights into the fraction of surface covered by wavelength-sized scatterers.

The Goldstone radar, if modified to become operational at X-band, would provide the only facility to observe Galilean satellites during the entire decade of the 1980s. These X-band observations would complement the existing Arecibo S-band data. In addition, the Goldstone radar could provide further data on Saturn's rings.

To complement the radar observations that are anticipated, a vigorous program of supporting theoretical and laboratory work is needed. For example, theoretical work on the polarization and high-angle scattering behavior of rough surfaces should be combined with high-quality laboratory experiments on the properties of analog materials to improve our ability to infer geologic characteristics from radar data. In terms of laboratory measurements, investigations of the radar reflectance properties of silicate/metal regolith analogs are needed urgently to fully interpret the accumulating set of asteroid observations.

## 9 Summary and Recommendations

### 9.1. Inner Solar System

#### 9.1.1. *Mercury*

In spite of Mariner 10's exploration, many important geologic questions remain unanswered. Mariner 10 imaged only about one-half of the planet (much of this coverage was at high sun angles and at resolutions poorer than 1 km) and did not provide any direct information on the composition of the planet's surface. Among the major geologic problems that remain to be resolved are (1) the origin of the plains deposits and (2) the nature of the global tectonics. Whether the plains are largely volcanic or whether they were produced by impact ejecta remains unresolved; the answer has profound implications for the geologic and thermal history of the planet. The global distribution of tectonic structures is also poorly known. The observed structures appear to result from compressive stresses, but their distribution and orientations are poorly determined, making it difficult to deduce the time of onset, duration, and probable cause of this compression. These and related important geologic questions could be addressed if global coverage of Mercury at a resolution of better than 1 km were obtained.

Other important unknowns about Mercury concern the composition of its surface and the present state of its interior. Models of planetary formation suggest that, due to its proximity to the Sun, the planet is enriched in iron and refractories and depleted in volatile materials relative to other Earthlike planets. Mercury's high mean density and intrinsic magnetic field suggest that the planet does have a large metallic core, but little if any precise information is available about the composition of the outer portions and surface



of the planet. There is also no information about the current physical state of the planet's interior. The extent to which Mercury's large metallic core remains molten today has important implications for the planet's thermal history as well as for models of how Mercury's magnetic field is maintained.

### **9.1.2. Venus**

Geologic studies of Venus remain fundamentally limited by our lack of information concerning the planet's surface. From more than a decade of spacecraft exploration (including Pioneer Venus altimetry and gravity measurements) and Earth-based radar observations, we have learned that Venus is a differentiated planet that is probably volcanically active today. Fundamental questions about Venus' geologic evolution persist:

1. What role, if any, have processes akin to plate tectonics played in molding the surface of Venus?
2. What are the ages of the surface units that we see?
3. Are any large impact basins preserved on the surface?
4. How important has volcanism been in the history of the planet?
5. Is there evidence of eolian transport of geologic materials?
6. Is there geologic evidence of an early epoch when liquid water was stable on the planet's surface?

Many of the continuing debates still associated with these and related questions would be resolved if global imaging of the planet's surface at a resolution of at least 1 km were available (this resolution is approximately equivalent to that of Mariner 9's coverage of Mars). Such coverage could be readily obtained by a mapping radar in orbit about the planet.

The evolution of Venus' atmosphere is also of great interest to planetary geology, not only because it determined the history of many important surface processes on the planet itself, but also because of the clues it provides to the nature, timing, and degree of outgassing of other terrestrial planets, including the Earth. It is essential to resolve the remaining discrepancies in the measurements and interpretations of the rare gas abundances in Venus' atmosphere. Some Pioneer Venus measurements have been interpreted to mean that Venus, like Earth, outgassed an ocean of water. Such models suggest that this water escaped primarily through

photodissociation, implying that large amounts of oxygen were somehow used up in weathering surface rocks. Such suggestions must be tested by detailed modeling and laboratory studies. In addition, laboratory studies of the chemical and weathering processes that might be occurring on the surface of Venus today are needed.

As the exploration of Venus continues, we will need to learn more about the surface and interior of the planet from in situ measurements. A concentrated effort is required to develop instruments that can operate sufficiently long in the hostile surface environment of Venus to return the desired measurements. Although chemical analyses can be made in a relatively short time, seismic experiments, our only means of learning directly about the internal state of Venus, will demand extended operational lifetimes. The technical problems to be solved are formidable; if operational Venus seismometers are to be available by the end of the century, development work must begin now.

### **9.1.3. Moon**

The Voyager investigations of the Galilean satellites have underscored the fact that much can be learned about the evolution of planets and satellites from the study of lunar-sized bodies. As the best studied object of this important class, and the only one for which we have an absolute chronology as well as returned samples that can be studied in detail in our laboratories, our Moon will continue to provide an essential reference point not only for our understanding of the smaller terrestrial planets but also for our work on other satellites and small bodies. The comparative geologic study of the Moon and of lunar-sized satellites can be expected to be a symbiotic process. For example, studies of our Moon have alerted researchers to the possibility that accretional energy may have been an important early heat source in the case of the Galilean satellites; on the other hand, the apparent efficacy of tidal heating in the case of Io has rekindled interest in this energy source during the early evolution of the Moon, when, according to most theories, our satellite was much nearer to Earth than it is today.

The Moon will also continue to be the focus of vigorous research in its own right. Among the many questions concerning the Moon that still need to be answered in detail are the following:

1. What are the precise characteristics and the causes of suspected crustal asymmetry between the near side and the far side?
2. What is the history of mare volcanism? What initiated the process, and why did it cease?
3. What influence did the formation of large impact basins have on the thermal structure and evolution of the Moon?
4. How did the earliest crust form? Was there a "magma ocean"?
5. What were the nature, timing, and extent of pyroclastic volcanism on the Moon?

#### **9.1.4. Mars**

Of all the objects in the solar system, Mars is perhaps the most similar to Earth in terms of many geologic surface processes. Although much has been learned as a result of the Mariner 9 and Viking missions of the 1970s, many fundamental questions remain to be answered. Some of these key questions concern the evolution of the martian surface and can in fact be addressed substantially using Viking data, which are available but which to date have not been fully reduced or analyzed. Thus, in the case of Mars, a major step in our understanding may be possible even before the next mission to the planet by a continuation of the steady, systematic analysis of accumulated data. Among the important geologic questions that such a systematic program of data analysis can address are:

*Cause of Hemispherical Dichotomy.* Most terrestrial planets show global heterogeneities, the patterns of which are roughly hemispherical. On Mars, the southern hemisphere consists predominantly of ancient cratered uplands, whereas the northern hemisphere is mostly younger, less cratered, lowland plains. What is the origin of this dichotomy, and when did it first develop? Did the resurfacing of the northern hemisphere involve only volcanic materials, or did sedimentary debris play an important role as well? In spite of its fundamental importance, no clear understanding of the reasons for the hemispherical dichotomy on Mars (or on other planets) is at hand.

*Volatile History.* Surface processes on Mars cannot be fully understood without clear definition of the present and past water cycles on the planet. How much water (and other volatiles) did Mars

outgas? When did this outgassing happen? Where is this water stored? At what rates can it be, and has it been, cycled among the likely reservoirs (ground, atmosphere, polar deposits)? How has the history of past water cycles affected valley development and regional denudation? Understanding the water cycles on Mars throughout the planet's history is fundamental to understanding the climatic, and consequently the history, of geologically important surface processes.

*Origin of the Canyon System.* Even though more than ten years have passed since Mariner 9 discovered Valles Marineris, we still lack good models of how this and related canyon systems formed. When did canyon formation begin on Mars? Was it a single continuous event, or was it a series of episodic phenomena? How closely is canyon formation related to volcanic and tectonic events? How was canyon development related to the complex of large outflow channels surrounding the Chryse basin? Answers to such questions are linked to models of the evolution of the interior of Mars and can be addressed using accumulated Viking data (images, topographic data, and IRTM\* measurements), as well as Earth-based radar altimetry.

*History of Polar Deposits.* It is widely believed that substantial amounts of volatiles are stored in the polar regions of Mars. Yet quantitative estimates, essential to models of climatic history and volatile evolution, are lacking. Further geologic studies of the complex laminated terrains and investigations of the causes of the evident asymmetry of the polar deposits between the south and north should lead to better models of the processes and cycles that were involved in producing the polar terrains. Such models should lead to quantitative estimates of the amounts of volatiles that are currently stored in the polar areas.

*Importance of Explosive Volcanism.* More than half the surface of Mars appears to be covered by volcanic materials, mostly lavas resulting from flood-type basaltic eruptions. Given the presence of water on Mars, it is reasonable also to expect explosive volcanism and attendant ash deposits. This may well be the origin of some of the extensive mantling plains units. Diagnostic criteria to distinguish ash deposits using imaging and other remote sensing data must be developed for application to Mars. The reliable identification of ash

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\*Infrared thermal mapper.

flows could provide important clues to understanding the volcanic history of Mars.

*Sedimentary History.* There is ample evidence that weathering and fluvial and eolian processes have been important throughout much of Mars' history. Accordingly, extensive sedimentary deposits (other than volcanic ash deposits) should exist. Given the evidence for climatic changes on Mars, how have sedimentary processes changed throughout the history of the planet? How have they affected the preservation of the cratering record? How can the sedimentary record be related to the denudational history of Mars? What remote sensing characteristics can be used to identify and map sedimentary deposits?

*Style of Tectonism.* Several areas of Mars, most prominently Tharsis and Elysium, show strong evidence of tectonic deformation. Despite several years of intensive study and mapping, fundamental questions regarding the stress fields involved and their time histories remain unresolved.

The questions outlined above provide examples of problems that can be addressed significantly, if not completely solved, with data available from previous missions and continuing Earth-based observations. There are other fundamental geologic questions about Mars, however, that will require future investigations by spacecraft. Most important among these are:

*Absolute Ages of Key Units.* Radiometric dating of rocks from key geologic units on Mars is essential to establish an absolute chronology for the planet.

*Current State of the Planet's Interior.* Direct determinations of the characteristics of the crust, mantle, and core are essential to models of the thermal, tectonic, and volcanic evolution of the planet. Improved models of this type should better constrain ideas about the history of volatiles on the planet.

*Composition and Mineralogy of Rocks in Key Units.* Remote sensing and Viking Lander measurements provide only indirect information on the composition and mineralogy of rock types on Mars. In part, this situation results from the limitations of the techniques used so far, but more fundamentally it derives from the fact that surficial measurements are sensitive only to the more or less ubiquitous weathering rind that appears to cover the very surface of the planet. Important questions include the nature of the unweathered materi-

als in various areas, as well as the rates, mechanisms, and products of weathering.

## **9.2. Outer Solar System**

Our discussion is divided into two parts, the first dealing with the satellites of Jupiter and the second with the satellites of Saturn. We expect that Voyager's investigations of the satellites of Uranus in 1986 and of Triton and perhaps other satellites of Neptune in 1989 will reveal many important geologic problems that will need thorough investigation. We have chosen to exclude any specific mention of planetary rings, since most of the investigations dealing with them have traditionally been supported by NASA programs other than Planetary Geology.

### ***9.2.1. Satellites of Jupiter***

Based on the diversity of geologic features and processes observed by Voyager, our recommendations for future studies of the Galilean satellites can be summarized as follows:

1. Terrestrial analogs of sulfur and water volcanism should be sought and intensively investigated. Several examples of sulfur volcanism are known on Earth. Analogs for resurfacing processes on icy satellites may also be found, possibly on terrestrial ice packs and glaciers.
2. The thermodynamic, mechanical, and rheologic properties of sulfur and of water ice must be determined precisely under pressure and temperature conditions applicable to the Galilean satellites. Such data are essential to the accurate modeling of internal and surface processes on these bodies.
3. Theoretical studies on possible eruptive mechanisms of sulfur and water-rich melts should be pursued vigorously.
4. Quantitative determinations of the relief of different surface features are urgently needed.
5. Detailed studies of structural relationships, particularly on Ganymede and Europa, are needed to better determine the nature and timing of the deformations these surfaces have experienced.
6. Accurate morphometric measurements of craters in various regions of Ganymede and Callisto are needed for comparison with craters on other solar system bodies as well as to

determine their possible evolution in time (due to changes in the crustal rigidity). The comparative studies should lead to a better understanding of the relative importance of such factors as gravity, target strength, etc., in controlling crater morphology.

Some of these recommendations have emphasized theoretical, analog, and modeling studies rather than detailed investigations of Voyager images. Although the Voyager mission established the general geologic style of each of the satellites, image resolution falls short of that needed for systematic geologic analysis, in which stratigraphic relations are determined and the history of action of different geologic processes is traced. Such data have been acquired for the Moon and Mars, but in the case of the Galilean satellites, they will become available only with future missions such as Galileo.

In addition to the Galilean satellites, Jupiter is accompanied by about a dozen smaller objects. The largest of these, Amalthea (Jupiter V) has a spectrophotometrically unusual surface and possibly an involved evolutionary history. Four small satellites (including Amalthea) are now known to exist inside the orbit of Io. All have ubiquitous low albedos and very red colors, probably resulting from contamination of the surfaces by sulfur derived from Io. There is also recent evidence that part of the orange color of Europa is due to sulfur contamination from Io. Theoretical studies of how material from Io is transferred throughout the inner satellite system are needed, as are laboratory simulations of the resulting implantation and regolith contamination processes.

#### ***9.2.2. Saturn Satellites***

Many of the geologic problems that should be addressed for the Saturn satellites system using the available spacecraft data are similar to those for the Galilean satellites. Our recommendations for future investigations include:

1. Thermal, eruptive, and tectonic histories of the small icy satellites should be delineated accurately. Clear evidence of global scale tectonics exists for Enceladus, Tethys, Dione, and perhaps Rhea, as does evidence of surface eruptions of fresh materials (ice). The time of these events must be clarified through crater counts and correlated with calculations of the thermal evolutions.

2. The possible role of ices other than water ice must be investigated. Although there is no direct evidence that any of the Saturn satellites (except Titan) accreted any ices other than water ice, even small amounts of ammonia would lower melting points significantly and lead to much more dramatic evolution scenarios for a given amount of internal energy.
3. Theoretical calculations are needed to determine the role of tidal heating for Enceladus, especially its time history. In this context, accurate calculations of the long-term variations of the eccentricity of Enceladus' orbit are required. Such studies should also try to determine why Mimas has apparently escaped similar tidal heating.
4. As in the case of Galilean satellites, accurate morphometry of surface features is required to obtain valid estimates of crustal strength and thereby constrain the time history of thermal evolution. Accurate morphometry of impact craters is also needed for intercomparison with similar data from other solar system objects. (Most of Saturn's satellites are low-gravity, icy bodies.)
5. Theoretical studies of the bombardment histories of the satellites must be pursued vigorously. We must ascertain whether it is likely that some of the inner satellites have been disrupted and reaccreted several times since the beginning of the solar system, as suggested by one popular model.
6. Remote sensing and theoretical studies of the possible connection of the E-ring with current internal activity of Enceladus should be supported.

Of all satellites in the Saturn system, Titan is almost certainly the most complex. Although Voyager obtained fundamental data on Titan's atmosphere, the nature of the satellite's surface remains unknown. In this context, high priority should be given to radar investigations of Titan's surface from spacecraft.

### **9.3. Small Bodies**

Due to their diversity and large numbers, the investigation of the small bodies presents special problems. Yet the thorough study of these objects is essential to an understanding of the processes that have shaped the evolution of our solar system. It is highly likely



that during the next ten years NASA will fly an exploratory mission to the small bodies; vigorous efforts must continue to develop appropriate instruments to maximize the data return from such a mission. Special attention must be given to instruments capable of determining the composition and mineralogy of surfaces remotely, as well as to techniques of automated sample collection and analysis. Methods of accurately mapping irregular objects and of determining precisely their masses and volumes also must be refined.

Since we cannot hope to explore most small bodies directly, remote sensing of such objects from Earth or Earth orbit will always remain an important part of planetary studies. Such investigations are needed to improve our knowledge of the physical characteristics of these bodies, as well as of their orbits and populations. These data will be needed to select the most attractive targets for future exploratory missions, as well as to improve our knowledge of the impact rates in different parts of the solar system.

#### **9.4. Geodesy and Cartography**

High-quality cartographic products and geologic maps should be prepared for all bodies for which adequate imaging is available. This effort is well under way but will require strong and continued financial support. With about twenty planetary bodies now imaged, the present cartographic backlog could extend for many years.

Improved radar images of Venus should be acquired to establish a control net of the planet and prepare a planetwide series of maps at a scale of approximately 1:5 000 000. The spacecraft should carry a radar altimeter for vertical control and interpretation of gravity field measurements.

In spite of numerous past missions to Mars, we still lack accurate altimetry of this important planet. We strongly urge that the next mission to Mars include a radar altimeter and that, if possible, the spacecraft be placed in a polar orbit. Altimetry and additional imaging of Mercury would also be of high interest to complete our reconnaissance of the Earthlike planets.

Given the likelihood of an exploration mission to one or more small bodies during the 1980s, the problems associated with mapping such generally irregular objects and precisely determining their sizes, shapes, and masses must be worked out in detail.

### 9.5. Laboratory Studies and Instrumental Techniques

Throughout this report we have emphasized that in order to take full advantage of future spacecraft missions, the continued development of appropriate instruments must be supported. Areas of major concern to planetary geology include remote sensing instruments (imaging systems, spectral mappers, mapping radars, etc.), as well as instruments required for in situ measurements (chemical and mineralogic analysis, age dating, seismic and thermal heat flow measurements). Particular attention must be paid to the development of automated sample collection techniques not only on Earthlike planets, but also on small bodies such as asteroids and comets. Also needed is the development of instruments that will function in very hostile environments such as at the surface of Io or Venus.

We expect that during the coming decade multispectral measurements will continue to provide much of the basic "compositional" information about surfaces of solar system bodies. In order that such data be interpreted as precisely as possible, a vigorous program of complementary laboratory studies should be supported. This program should investigate how such spectra are determined not only by the mineral composition of the surface, but also by particle size, surface texture, and roughness, and especially the effects of mixing. Additional complications that must be understood include the effects of photometric geometry and, in the case of outer planet satellites, the effects of low temperature and intense charged particle radiation.

It is abundantly clear that the nature and rates of weathering processes on a planet are critically dependent on the temperature, pressure, and composition of the planet's atmosphere. Careful laboratory studies of the chemical and physical weathering processes to be expected on Mars, Venus, Io, Titan, etc., should be performed. Not only do we need to know the nature of the weathering processes and their end products, but, most importantly, we need information on their rates under the conditions that apply to the planets in question. Such "environmental chamber" studies can also be used to determine the rates of various other atmosphere/regolith interactions, for example, the ability of the martian regolith to store volatiles and to buffer atmospheric pressures.

Because of the obvious significance of eolian processes on Mars and their probable importance on Venus, wind tunnel investigations of sediment transport and erosion rates on these two planets should continue.

Past laboratory studies have been especially successful in elucidating the mechanics of impact cratering in silicate rocks. With the recent Voyager exploration of many low-density, icy bodies, it is essential to extend laboratory cratering studies to ice and other low-density targets (e.g., ice-silicate regolith mixtures). Concurrent with these impact studies, accurate determinations of the rheologic and general mechanical properties of various ices are needed as a function of temperature. In the context of understanding the cratering and tectonic histories of the icy satellites, such studies should pay special attention to the properties of mixtures of ices and ices contaminated with silicates.

Investigations of available extraterrestrial samples (Moon, rocks, meteorites, and cosmic dust) should be vigorously pursued.

#### **9.6. Analog Studies**

As a first step in the identification of different geologic provinces on extraterrestrial bodies, one relies on morphologic appearance. Cleverly designed terrestrial analog studies will go a long way toward revealing the dominant processes responsible for the evolution of various multicomponent land features and also in providing quantitative estimates of the magnitudes, frequencies, and intensities of the events responsible. A broad spectrum of analog studies should continue to be supported both on subaerial features and on some submarine features on the continental slopes. In a few key areas, such as possible analogs of sulfur and water volcanism on outer planet satellites and those of valley networks on Mars, efforts should be accelerated.

#### **9.7. Remote Sensing from Earth**

In spite of occasional spacecraft missions, we expect that remote sensing observations from Earth and Earth orbit will continue to play a fundamental role in planetary science during the coming decade. In some cases (volcanic activity on Io, dust storms on Mars), such observations will provide essential extended coverage of time-variable phenomena. In other cases (for example, high spatial resolution spectral observations of the Moon), they will con-

tinue to yield basic data needed to support ongoing research. In particular, they will continue to provide the bulk of our information on the fluxes and photometric and orbital characteristics of the multitude of small bodies in our solar system.

Earth-based radar observations, both at Arecibo and Goldstone, can be expected to continue producing important data on the topography and roughness characteristics of the terrestrial planets. In addition, radar studies of asteroids and comet nuclei should begin yielding new information on the surface characteristics (e.g., metal/silicate ratio in the case of asteroids) of these little-known bodies.

### **9.8. Remote Sensing of Earth**

Observations of the surface of Earth from orbiting satellites, Skylab, and the Space Shuttle provide a superb data base for a multitude of applications in planetary geology. Among the many possible investigations of high interest to planetary geology are the following:

1. Radar studies of different terrain types and geologic units for correlation with planetary radar data.
2. Continuation of multispectral observations, from visible to near infrared, to search for geochemical and petrologic signatures of various terrestrial geologic provinces. Such studies should be related closely to current laboratory spectral investigations (discussed above) as well as to ground truth observations.
3. Multispectral terrestrial data sets, landform maps, and gravity and aeromagnetic maps should be put into a mutually compatible computer format, akin to the Lunar and Mars Consortia data sets. Such data would permit testing of spatial correlation techniques, such as those now being used for Mars, on terrestrial features where deduced cause-and-effect relationships can be independently verified by field observations.

### **9.9. Archiving and Dissemination of Planetary Data**

Continuing attention must be paid to the problem of archiving and disseminating data obtained from past planetary missions. In certain cases, some of these data remain to be thoroughly analyzed (for example, many of the Viking Orbiter images of Mars). In other

cases, such past data will provide valuable comparisons with information expected in the future (for example, the comparison of Voyager images of Io with those to be obtained by Galileo). During the past five years, the network of Regional Libraries set up by the Planetary Geology Program across the United States has played a crucial role in preserving and making available to investigators the imaging products (and related data sets) from past planetary missions. The PGWG considers the Regional Libraries an essential part of the Planetary Geology Program and urges continued support and, if possible, expansion of the system.

#### **9.10. Continuity and Future of the Planetary Geology Program**

During the past two decades, the Planetary Geology Program has made impressive contributions to our understanding of our solar system. There is every reason to expect that these contributions will continue during the next decade, provided that NASA plans adequately for the maintenance and healthy modest growth of the enterprise. Efforts must be increased to ensure that adequate data analysis funds are available to support recent and future planetary exploration. Steady and predictable support is needed to ensure that planetary geologists can use state-of-the-art instrumentation and techniques to carry out their tasks. Short-term fluctuations in the level of support, such as those witnessed during the early 1980s, could be avoided by long-range planning, given NASA's continuing commitment to the solar system exploration program in general, and the Planetary Geology Program in particular.

NASA's plans for the future exploration of the solar system include several missions of high interest to planetary geology. Efforts must continue to ensure that adequate support is available to design and fabricate the best state-of-the-art instruments and data handling systems for these endeavors.

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